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CORPS OF ENGINEERS, U. S. ARMY

EFFECTS OF EXPLOSIONS IN SHALLOW WATER

REPORT NO. 6

CRATERING EFFECTS IN SAND, SURFACE WAVES, AND AIR-BLAST MEASUREMENTS FOR A SCALED WATER DEPTH OF 200 FT.

CONDUCTED FOR

ARMED FORCES SPECIAL WEAPONS PROJECT
DEPARTMENT OF DEFENSE

AND

THE CHIEF OF ENGINEERS
DEPARTMENT OF THE ARMY

BY THE

WATERWAYS EXPERIMENT STATION
VICKSBURG, MISSISSIPPI

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PREFACE

This is the sixth report in a series to be published on the study of "Effects of Explosions in Shallow Water" being conducted for the Armed Forces Special Weapons Project, Department of Defense, and the Corps of Engineers, Department of the Army, by the Waterways Experiment Station. The study is concerned with scaled explosions of 20 kilotons of TNT in water depths of 30, 60, 100 and 200 ft. Reports are published intermittently to describe a completed phase or series of tests. At the end of the study, a final report will be prepared which will attempt to correlate and summarize the results of the entire testing program.

This report describes: (a) the results of field tests conducted in an isolated area south of Vicksburg, Mississippi, to determine the cratering effects in sand and record the height of surface water waves; and (b) the results of air-blast measurements made both in the field and at the Waterways Experiment Station test site. The results of all tests were made for conditions of a scaled water depth of 200 ft. The data on cratering and surface water waves are an extension of the test results presented previously in Report No. 3 with smaller charge weights.

A list of reports in preparation or published, to date, is printed on the inside of the front cover for the information of the reader. Symbols and the less familiar abbreviations used throughout this report are defined on pages 17 and 18.

EFFECTS OF EXPLOSIONS IN SHALLOW WATER

REPORT NO. 6

Cratering Effects in Sand, Surface Waves and Air-Blast Measurements for a Scaled Water Depth of 200 Feet

Introduction

1. Reported herein are the results of a series of small-scale tests to determine the cratering effects in sand and the magnitudes of surface water waves and air blast caused by an explosion of 20,000 tons of TNT in a water depth of 200 ft. Tests to measure air blast with charge weights up to 32 lb were conducted at the Waterways Experiment Station. Charge weights of 32 lb and larger were fired at a field-test site about 10 miles south of Vicksburg, Mississippi. A description of the WES test site, similitude considerations, and testing procedures are contained in Report No. 1*. A description of the field-test site is contained in Report No. 5. This information is repeated briefly herein for the convenience of the reader.

Description of Test Sites

2. Tests with charge weights of 32 lb, or less, were conducted on the Waterways Experiment Station reservation in a keyhole-shaped basin (designated herein as "WES test basin"). The basin was excavated to an approximate depth of 5 ft in undisturbed loess soil. A pit approximately 60 ft long, 20 ft wide and 5 ft deep was excavated in the circular portion of the test basin, and was filled with sand to provide the proper

* See list of reports on inside of front cover.

bottom material. The field tests using charge weights up to 2048 lb were conducted about 10 miles south of Vicksburg, Mississippi, in an old channel of the Mississippi River near Diamond Point Cutoff. The deep deposits of sand in the form of long, flat bars along an isolated section of the old river bed provided an excellent test site for the firing of large charges.

Similitude Considerations

3. The principle of similarity, generally accepted for explosive work with scaled charges, states that if the linear size of a charge be changed by some factor k , the pressure condition will be unchanged if the scales of distance and time are changed by the same factor. That is, pressure conditions or the magnitudes of other physical phenomena associated with an explosion can be written as functions of distance and time for any explosion once they are known for a specific explosion, by scaling all distances and times in accordance with the ratio of the linear sizes of the two charges. The cube root of the charge weight ($W^{1/3}$) is used as a convenient measurement of linear size.

4. The depth of water used in the tests was therefore based on the ratio, $D/W^{1/3}$, which, for the prototype depth of 200 ft and the charge weight of 20,000 tons, is 0.585. Actual water depths used in the tests were 0.46, 0.93, 1.47, 1.85, 3.71, and 7.42 ft for charge weights of 0.5, 4, 16, 32, 256, and 2048 lb, respectively.

Test Conditions and Procedures

5. The study of explosions in shallow water involves the

determination of effects of exploding 20,000 tons of TNT in water depths of 30, 60, 100, and 200 ft on (a) cratering in various soils, (b) air blast, (c) shock waves in water and earth, and (d) surface water waves. Initial tests were concerned with cratering effects in loess soil and measurements of surface water waves. Results of these tests for scaled water depths of 200 ft and 30 ft are contained in Reports Nos. 1, 2, and 4. The tests reported upon herein were concerned with cratering effects in sand and measurements of surface water waves and air blast for a scaled water depth of 200 ft. Cratering effects in sand and surface-wave measurements were obtained at the field-test site. Measurements of air blast were obtained at both the WES test basin and the field site.

6. The test-charge weights, except the 16-lb charge, were so selected that the magnitudes of all physical phenomena would be reduced or increased by a factor of 2. That is, the same blast pressures would exist for the 0.5-lb charge (1/8 the weight) as for the 4-lb charge at half the distance and time; the same blast pressure would exist for the 32-lb charge (8 times the weight) as for the 4-lb charge at twice the distance and time. The 32-lb charge was the largest that could be detonated on the Waterways Experiment Station reservation because of the location of the test basin with respect to residential areas. Charges of 16 lb were made up with standard Corps of Engineers 1-lb TNT demolition blocks. Spherically-shaped charges of cast TNT were used for test-charge weights of 0.5, 4, 32, and 256 lb. Diameters of the spheres were 0.215, 0.432, 0.863, and 1.725 ft for the 0.5-, 4-, 32-, and 256-lb charges, respectively. The charge of 2048 lb was built up in the shape of a cube with 100-lb blocks of cast TNT and Corps of Engineers 1-lb demolition blocks.

Waterways Experiment Station test site

7. Procedures for tests conducted on the Waterways Experiment Station reservation differed from those described in Report No. 1 in that only air-blast measurements were obtained. The basin was graded level in the test area to insure that bottom conditions were the same for each shot, and charge locations were fixed, prior to flooding the basin, by placing wood stakes at safe distances on a rectangular grid. Lengths of steel pipe were driven into the bottom to locate and support the air-blast gages. Air-blast pressures were measured with tourmaline piezoelectric gages which were 7/8, 1-1/8, and 1-5/8 in. in diameter. The gages were mounted 1 ft above the water surface at reduced distances (λ)* of 6, 10, 15, and 20 from the charge with the face of the gage parallel to the path of the pressure wave. Blast pressures were recorded on 10-in. strips of 35-mm film with rotating-drum cameras mounted on Dumont, type 304H, cathode-ray oscilloscopes.

8. Tests in the WES test basin included charges fired at scaled depths of 45 and 90 ft below the bottom, at the bottom, at mid-depth, at the water surface, and at one-half the water depth above the water surface. The 32-lb charge was not fired in the latter two positions because of complaints from nearby residents; instead 16-lb charges were used to extend the range of data in these charge positions. The center of gravity of the charge was used as the reference for charge position. Three to five identical charges were fired in each position to insure that test data were reliable.

* $\lambda = R/W^{1/3}$

9. The test basin was flooded to the proper depth after the charge locations had been fixed and air-blast gages mounted. Electrical cables connected the air-blast gages to recording equipment in the instrument building. It was necessary to support blast-gage cables above the water surface to eliminate "cable signal" produced by either water or earth shock. The test area was then cleared of personnel and the charge was placed in the basin at the desired position and prepared for detonation. The charge was fired from the instrument shelter by means of an electrical circuit which was synchronized with control circuits of the air-blast recording equipment*. Air-blast measurements were recorded during the detonation process, and still and motion pictures of the surface phenomena were also made for a representative number of shots.

Field-test site

10. Procedures for conducting tests with the large charges in the old river channel south of Vicksburg were generally the same as those followed at the WES test basin. Instrumentation equipment and portable generators for electrical power supply were housed on a 20-ft by 48-ft steel barge anchored from 800 to 1000 ft from the charge location. A minor modification of air-blast equipment was made in that cathode followers were placed in the circuit about 200 ft from the tourmaline gages to overcome the loss of signal strength due to the additional cable length required.

11. Charge locations were selected to provide the proper water depth and a fairly level bottom extending a distance from the charge

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* Details of instrumentation for the project will be the subject of a later report.

sufficient to place gages and wave rods. The locations and spacings of the air-blast gages were fixed by the scaled distances used at the WES test basin and described in paragraph 7. Wave rods were placed on a line radiating from the charge position at scaled distances of R/D = 10, 20, 40, and 60, where R is the actual distance in feet from the charge and D is the actual depth of water in feet. These distances correspond to those used previously in the tests with smaller charges described in Report No. 3.

12. Tests at the field site included: (a) 32-lb charges fired at the bottom, at mid-depth, at the water surface, and at 0.5D above the water surface; (b) 256-lb charges fired at the bottom and at mid-depth; and (c) a 2048-lb charge fired at the bottom. The center of gravity of the charge was used in all tests as the reference for charge position. At least two identical charges were fired in each position with the exception of the 2048-lb charge where only one shot was fired.

13. Crater measurements were made by placing a 100-ft metallic tape across the center of the crater and taking level-rod readings at 6-in. intervals along the tape. At least two representative profiles at right angles to each other were obtained in this manner.

Cratering Test Results

Test data

14. Test results of cratering presented herein pertain primarily to the larger charges fired at two charge positions, bottom and mid-depth. In order to correlate these data with results obtained with the smaller charges at the same positions, test results for the latter have been

taken from Report No. 3.

15. The results obtained from field tests of cratering in sand using 32-, 256-, and 2048-lb charges for a scaled water depth of 200 ft are summarized in table 1. Crater dimensions listed in the table were obtained from plots of crater profiles and relate to the apparent crater only. Reduced or scaled crater dimensions, defined as the dimensions in ft divided by the cube root of the charge weight in pounds, are also listed in the table.

16. Listed in table 2, for the two charge positions, are two separate values of K and n * determined first by averaging the reduced crater dimensions in table 1 and in tables 2-4 of Report No. 3, and second, by computing the values of K and n for the various parameters from the crater dimensions using the method of least squares. Results of the 0.5-lb charges were not considered in arriving at the values of K and n listed in table 2.

17. Photograph 1 is a view of the crater formed by the 2048-lb charge detonated at the bottom. The photograph was made one week after the charge was fired, during which time the river stage had fallen sufficiently to expose the crater limits.

18. Plates 1 and 2 show half-crater profiles representing the average of all crater soundings for each charge weight and position. Each plotted point represents the average of four separate soundings obtained at equal radial distances from the charge. Shown also on the plates in tabular form are the values of the six crater measurements of major

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* Where K and n are elements of the empirical equation $P = KW^n$.

importance: depth, width, lip height, lip width, area, and volume.

19. Plates 3-6 show plots of the average values of various crater dimensions versus charge weight. Values of the plotted points for the 32-, 256-, and 2048-lb charges (field tests) were taken from plates 1 and 2, while results for the 0.5-, 4-, 16-, and 32-lb charges (WES basin tests) were taken from plates 5-8 and 10, Report No. 3. Plate 3 shows the effect of charge weight on crater depth for charges positioned on the bottom (Z = -1.0D) and at mid-depth (Z = -0.5D). The equations of the lines best fitting the respective experimental points were determined by the method of least squares. A similar procedure was followed in developing the plots presented on plates 4-6 for crater width, area and volume. The data for the 0.5-lb charges were not used in developing the empirical equations shown on each plate in view of the apparent disagreement with results obtained with the larger charge weights, particularly for crater width, area and volume.

20. Plates 7 and 8 show dimensionless plots of the half-crater profiles for each charge position. In the plot of X/r versus Y/d the ordinate is a ratio of crater depth at any point to the depth at ground zero, and the abscissa is a ratio of radial distance from the charge to the crater radius (X/r). Shown also in dimensionless form is the plot of $X/W^{1/3}$ versus $Y/W^{1/3}$, where X is the radial distance from the charge, Y is the crater depth at the radial distance X, and $W^{1/3}$ is the cube root of charge weight.

Discussion of results

21. The trend of results, summarizing the WES-basin and field-site cratering tests in sand for a scaled water depth of 200 ft, indicates

fair agreement with the cube-root-of-charge-weight law. Crater depth (plate 3) varied at $W^{0.40}$ and $W^{0.44}$ for charges positioned at bottom and mid-depth, respectively. The crater depth for a charge positioned at mid-depth was approximately eight-tenths that of a charge positioned at the bottom. An approximation of the crater depth for TNT charges positioned at or near the bottom may be computed from the equation, $d = (0.54 \pm 0.06)\, W^{1/3}$.

22. Crater width was only slightly affected by charge position (plate 4), and varied as $W^{0.30}$ and $W^{0.36}$ for charges positioned at bottom and mid-depth, respectively. The width of crater for TNT charges at or near the bottom may be computed from the equation, $w = (3.49 \pm 0.37)\, W^{1/3}$. Crater area and volume varied approximately as $W^{0.8}$ and $W^{1.12}$, respectively.

23. Consistent with the findings of Report No. 3, a definite crater lip was formed when the charge was positioned at the bottom; however, the height of the lip was insignificant when compared to the water depth. No lip was formed when the charge was positioned at mid-depth.

Surface Water Waves Test Results

Test data

24. Wave results reported upon herein extend the data previously presented in Report No. 3 to include results obtained from the larger charges fired at mid-depth and at the bottom during the field tests described in paragraphs 10-12. Results are shown on plates 9-12; plates 36, 39, 42, and 45 of Report No. 3 present similar data with smaller charges.

25. Plate 9 shows the variation of first-crest height with distance from the charge for the various charge weights and the two charge positions. Similar plots for first-crest height plus depth of first trough are shown on plate 10. Since these data indicate straight-line plots on logarithmic scales, it was assumed that an equation of the general form, $a = KR^n$, was applicable, where a is either the crest height (a_{+1}) or the combined crest to trough distance $(a_{+1} + a_{-1})$. K is a factor pertaining to charge weight and position; R is the horizontal distance from the charge, and n is an exponent indicating the rate of wave-height decay. The average rates of decay between gages at $R/D = 10$ and $R/D = 60$ were determined by computing the values of the exponent, n, by the least-squares method. The values thus obtained from the field tests were added to tables F and G, Report No. 3, and the combined results are presented in tables A and B below.

Table A

VALUES OF "n" FROM EQUATION $a_{+1} = KR^n$

Charge Weight (W)	Charge Positions (Z) 0.5D	0	-0.5D	-1.0D	-1.225D	-1.45D
0.5	-1.09	-0.93	-1.18	-1.14	-0.97	-0.89
4	-0.57	-0.75	-0.98	-1.23	-0.98	-0.67
16	-0.79	-0.62	-0.88	-0.97	-0.96	-0.91
32	-0.78	-1.29	-0.96	-1.00	-0.88	-0.96
256	-----	-----	-0.74	-0.81	-----	-----
2048	-----	-----	-----	-0.86	-----	-----

Average value, n = -0.92

Table B

VALUES OF "n" FROM EQUATION $a_{+1} + a_{-1} = KR^n$

Charge Weight (W)	Charge Positions (Z)					
	0.5D	0	-0.5D	-1.0D	-1.225D	-1.45D
0.5	-0.86	-0.86	-0.96	-0.88	-0.86	-0.95
4	-0.77	-0.76	-0.96	-1.17	-0.87	-0.83
16	-0.82	-0.97	-0.88	-0.90	-0.89	-0.88
32	-0.62	-1.12	-0.96	-0.86	-0.77	-0.89
256	-----	-----	-0.55	-0.95	-----	-----
2048	-----	-----	-----	-0.80	-----	-----

Average value, n = -0.87

26. The values of n presented in the previous tables were in the same range as those procured for the smaller test-charge weights. Also, the data indicate that the first wave decreases in height in an almost direct ratio as the distance from the charge.

27. Plate 11 shows the variation of first-crest height with charge weight at the various scaled distances (R/D) and the two charge positions. Similar plots for first-crest height plus depth of first trough are shown on plate 12. The linear plots again indicate an equation of the general form, a_{+1} or $a_{+1} + a_{-1} = KW^n$. Values of n were computed by the least-squares method for the plots on both plates and are shown in tables C and D below; the tables also include data presented previously in tables H and I, Report No. 3.

Table C

VALUES OF "n" FROM EQUATION $a_{+1} = KW^n$

	Charge Positions (Z)					
R/D	0.5D	0	-0.5D	-1.0D	-1.225D	-1.45D
10	0.13	0.19	0.21	0.13	0.12	0.29
20	0.29	0.19	0.15	0.30	0.21	0.37
40	0.32	0.14	0.23	0.32	0.20	0.34
60	0.32	0.22	0.29	0.34	0.15	0.24
Avg	0.26	0.18	0.22	0.27	0.17	0.31

Average of all values, n = 0.24

Table D

VALUES OF "n" FROM EQUATION $a_{+1} + a_{-1} = KW^n$

	Charge Positions (Z)					
R/D	0.5D	0	-0.5D	-1.0D	-1.225D	-1.45D
10	0.20	0.09	0.15	0.22	0.17	0.23
20	0.28	0.20	0.20	0.21	0.22	0.28
40	0.30	0.17	0.27	0.27	0.23	0.27
60	0.16	0.22	0.30	0.25	0.18	0.25
Avg	0.24	0.17	0.23	0.24	0.20	0.26

Average of all values, n = 0.22

28. The average of all values of n indicates that wave height varied approximately as the fourth root of charge weight ($W^{0.25}$), although individual values deviated slightly from the over-all average. Values of K in the equation $a_{+1} + a_{-1} = KW^n$ were computed for n = 0.25, and are

compared in table E with similar computations for wave heights resulting from Test Baker at Bikini. The most favorable agreement with Test Baker wave heights was obtained when the TNT charges were detonated at the water surface (Z = 0, in table E).

Table E

COMPARISON OF VALUES OF K IN EQUATION $a_{+1} + a_{-1} = KW^{0.25}$

FOR TEST BAKER AND WES TESTS

		WES Charge Positions (Z)					
R/D	Baker*	0.5D	0	-0.5D	-1.0D	-1.225D	-1.45D
10	0.59	0.42	0.56	0.40	0.41	0.45	0.45
20	0.30	0.26	0.32	0.20	0.20	0.24	0.32
40	0.16	0.13	0.17	0.12	0.12	0.13	0.15
60	0.11	0.09	0.13	0.09	0.08	0.10	0.11

* Charge detonated at mid-depth (Z = -0.5D)

Discussion of results

29. Incorporation of the results of the field-test shots with results presented in Report No. 3 indicated, as previously reported, that when the ratio $D/W^{1/3}$ was in the range of 0.585, maximum wave heights occurred when the charge was detonated at or near the water surface, and that wave heights varied directly as a function of the fourth root of charge weight ($W^{0.25}$) at constant scaled distances (R/D) from the charge. Wave heights decreased almost directly with an increase in distance from the explosion.

30. All wave measurements have been made with uniform water depths

throughout the range of measurements. The application of these data for the scaled 200-ft water depth to a particular harbor must, therefore, take into consideration the effects on wave dimensions of harbor geometry and hydrography. This may require additional model studies; however, it is believed that in many instances the charting of waves within a harbor will be possible by the use of refraction and diffraction diagrams.

Air Blast Test Results

Test data

31. The air-blast records obtained from charges fired with a scaled water depth of 200 ft and a sand bottom were analyzed in accordance with procedures described in Report No. 5 for tests in the scaled 30-ft water depth. Results of air-blast measurements are presented in tables 3-14. Tables 3-11 present the results of shots fired in the WES test basin and tables 12-14 present the results of field-test shots. Shot numbers are repeated in the tables when more than one gage was located at the same distance from the charge. Tabulations of results were limited to charges fired above the surface, at the surface, and at mid-depth, inasmuch as pressures recorded for charges detonated on the bottom were below the 1-psi level at $\lambda = 6$, and less than 0.5 psi at $\lambda = 20$. Computations required for the complete tabulation of pressures for this charge position were not made in view of these results.

32. Plate 13 shows the variation of air-blast peak pressure with reduced distance for the three charge positions at which pressures of significant magnitudes were obtained. The plotted points represent the average peak pressures for each charge weight. The curves and accompanying

equations were computed by combining the average peak pressures for all charge weights and their respective reduced distances in the method of least squares.

33. Plate 14 shows the effect of charge position on peak pressure; plots of peak pressure versus reduced distance, for the various charge positions, are presented together for comparison. The plotted points represent the average peak pressures for all charge weights which were used in computing the equations for the curves. A similar treatment of reduced positive impulse is presented on plates 15 and 16.

Discussion of results

34. A comparison of peak-pressure and reduced-impulse data for the various charge weights listed in tables 3-14 indicates that test results agree closely with the accepted scaling law (paragraph 3). Charges detonated at a scaled distance of 100 ft above the water surface $(Z = 0.5D)$ yielded air pressures at $\lambda = 6$ about 1.6 times those for a surface burst; however, pressures for both positions were the same at $\lambda = 20$ (plate 14). Charges fired at the scaled 100-ft depth $(Z = -0.5D)$ produced pressures comparable to those resulting from charges detonated at a scaled distance of 90 ft below bottom in the 30-ft water depth, Report No. 5. Plates 17 and 18 present a direct comparison of results obtained from charges fired at similar positions with respect to the water surface. Plate 17 shows the curves resulting from air-blast peak-pressure measurements for charges fired at the surface in both the scaled 30- and 200-ft water depths, and for charges fired at 90 ft below the bottom (120 ft below the water surface) in the 30-ft water depth and at mid-depth (100 ft below the water surface) in the 200-ft water depth. Plate 18 shows the reduced positive

impulse curves for the same test conditions. Variations between comparable plots are not significant enough to indicate a real difference in results.

Abbreviations and Symbols

A cross-sectional area of crater in sq ft

a_{+1} crest height of first surface wave in ft

a_{-1} trough depth behind first surface wave in ft

$a_1 = a_{+1} + a_{-1}$

a_{+2} crest height of second surface wave in ft

a_{-2} trough depth behind second surface wave in ft

$a_2 = a_{+2} + a_{-2}$

c celerity or velocity of the surface wave in ft per sec

D depth of water in ft

d maximum depth of apparent crater in ft (after collapse of crater lip)

h height of crater lip in ft

I positive impulse in lb-ms per sq in.

m milli

ms millisecond

P any parameter in the general empirical formula $P = KW^n$, where K is a constant and n is the exponent of W

p peak pressure in lb per sq in.

R horizontal distance from charge in ft

r radius of crater ($w/2$) in ft

S standard deviation of a single observation ($\pm$)

$S(\%)$ S, expressed as a percentage ($\pm$)

S_m standard deviation of the mean ($\pm$)

$S_m(\%)$ S_m, expressed as a percentage ($\pm$)

t time in sec

Abbreviations and Symbols (Cont'd)

V volume of crater in cu ft

W value of energy release, or weight of charge in lb

w width of crater in ft

w' width of crater lip in ft

X, Y standard rectangular coordinates from any designated point of origin in ft

Z charge position, distance from water surface to charge center of gravity expressed in terms of the total water depth

λ $R/W^{1/3}$ (reduced distance)

μ micro

PHOTOGRAPHS

Crater formed by 2048-lb charge detonated at bottom. Scaled water depth, 200 ft

PHOTOGRAPH 1

TABLES

TABLE 1

RESULTS OF CRATERING TESTS IN SAND - FIELD TESTS

$D/W^{1/3} = 0.585$

Charge Position (Z)*	Shot No.	Water Depth D(ft)	Crater Dimensions: Max Depth d (ft)	Max Width w (ft)	Height of Lip h (ft)	Width of Lip w' (ft)	Reduced Crater Dimensions: $d/W^{1/3}$	$w/W^{1/3}$	$h/W^{1/3}$	$w'/W^{1/3}$
32-LB CHARGES										
Charge at Bottom	412	1.85	**	**	**	**				
(Z = -1.0D)	413	1.85	1.80	10.0	0.40	5.00	0.57	3.14	0.13	1.57
256-LB CHARGES										
Charge at Bottom	415	3.71	3.88	24.5	0.31	7.75	0.61	3.86	0.05	1.22
(Z = -1.0D)	416	3.71	3.93	24.5	0.37	7.75	0.62	3.86	0.06	1.22
Arithmetic mean		3.71	3.90	24.5	0.34	7.75	0.61	3.86	0.05	1.22
Charge at Mid-Depth	417	3.71	3.80	23.0			0.60	3.62		
(Z = -0.5D)	418	3.71	3.09	25.0			0.49	3.94		
Arithmetic mean		3.71	3.45	24.0			0.54	3.78		
2048-LB CHARGE										
Charge at Bottom (Z = -1.0D)	420	7.43	8.10	49.1	1.93	25.4	0.64	3.87	0.15	1.76

* Charge Position (Z) denotes, in terms of total water depth (D), the distance above or below the water surface to the charge center of gravity.
** No data obtained.

TABLE 2

RESULTS OF CRATERING TESTS IN SAND

WES BASIN* AND FIELD TESTS

$D/W^{1/3} = 0.585$

Crater Parameter**	Mean Values for $W^{1/3}$ Law K	Mean Values for $W^{1/3}$ Law n	Mean Experimental Values K	Mean Experimental Values n
	Charge At Bottom (Z = -1.0D)			
Width - w	3.49	0.33	3.10	0.36
Depth - d	0.54	0.33	0.36	0.40
Area - A	1.11	0.67	0.62	0.80
Volume - V	2.17	1.00	1.07	1.17
	Charge At Mid-Depth (Z = -0.5D)			
Width - w	3.72	0.33	4.07	0.30
Depth - d	0.41	0.33	0.28	0.44
Area - A	0.80	0.67	0.51	0.79
Volume - V	1.52	1.00	1.14	1.07

* Results obtained with the 0.5-lb charges were omitted.
** $P = KW^n$ where:

- P = specified parameter
- K = constant
- W = charge weight in lbs
- n = exponent of charge weight

Charge position (Z) denotes, in terms of total water depth (D), the distance above or below the water surface to the charge center of gravity.

TABLE 3

RESULTS OF AIR-BLAST MEASUREMENTS - 0.5-LB CHARGES

$D/W^{1/3}$ = 0.585; BOTTOM MATERIAL - SAND

CHARGE POSITION - ABOVE SURFACE (Z = 0.5D)

Gage Distance (ft)	Reduced Distance λ (ft/lb$^{1/3}$)	Shot No.*	Peak Pressure (psi)	Positive Impulse (lb-ms/in^2)	Reduced Positive Impulse (lb-ms/in^2/lb$^{1/3}$)	Positive Duration (ms)	Negative Impulse (lb-ms/in^2)	Negative Duration (ms)	Arrival Time (ms)	Avg Velocity Charge to Gage (ft/sec)	Avg Velocity Gage to Gage (ft/sec)
4.76	6	486	21.6	7.86	9.86	1.25	10.4	7.00	1.05	4530	
		486	24.8	9.01	11.4	1.18	9.74	6.74	1.20	3970	
		487	22.3	8.84	11.1	1.30			1.06	4490	
		487	27.0	8.68	10.9	1.07	18.8	9.20	1.28	3720	
Arithmetic mean			23.9	8.60	10.8	1.20			1.15	4180	
S			±2.5	±0.50	±0.66	±0.10			±0.12	±400	
S (%)			±10	±5.8	±6.1	±8.3			±10	±9.6	
S_m			±1.2	±0.25	±0.33	±0.05			±0.06	±200	
S_m (%)			±5.0	±2.9	±3.0	±4.2			±5.2	±4.8	
7.94	10	486	8.60	5.80	7.31	1.85	6.34	7.37	3.12	2540	1540
		486	9.06	5.56	7.01	1.98	3.81	5.01	3.16	2510	1620
		487	8.11	5.28	6.65	1.74	6.57	7.71	3.12	2540	1540
		487	8.83	5.61	7.07	1.88	8.06	9.01	3.26	2440	1610
Arithmetic mean			8.65	5.56	7.01	1.86			3.16	2510	1580
S			±0.40	±0.22	±0.28	±0.10			±0.06	±48	±44
S (%)			±4.6	±4.0	±4.0	±5.4			±1.9	±1.9	±2.8
S_m			±0.20	±0.11	±0.14	±0.05			±0.03	±24	±22
S_m (%)			±2.3	±2.0	±2.0	±2.7			±0.9	±1.0	±1.4
11.91	15	486	4.18	3.75	4.72	2.28	3.58	7.61	5.94	2000	1420
		487	4.17	4.13	5.20	2.50	2.31	6.75	6.05	1970	1390
Arithmetic mean			4.18	3.94	4.96	2.39			6.00	1980	1400
15.87	20	486	3.05	3.14	3.96	2.81	2.33	6.74	9.24	1720	1200
		487	2.92	3.18	4.01	2.68	2.72	7.82	9.23	1720	1240
Arithmetic mean			2.98	3.16	3.98	2.74			9.24	1720	1220

* Shot number repeated where more than one gage used at a particular location.

TABLE 4

RESULTS OF AIR-BLAST MEASUREMENTS - 0.5-LB CHARGES

$D/W^{1/3} = 0.585$; BOTTOM MATERIAL - SAND

CHARGE POSITION - AT SURFACE (Z = 0)

Gage Distance (ft)	Reduced Distance λ (ft/lb$^{1/3}$)	Shot No.*	Peak Pressure (psi)	Positive Impulse (lb-ms/in^2)	Reduced Positive Impulse (lb-ms/in^2/lb$^{1/3}$)	Positive Duration (ms)	Negative Impulse (lb-ms/in^2)	Negative Duration (ms)	Arrival Time (ms)	Avg Velocity Charge to Gage (ft/sec)	Avg Velocity Gage to Gage (ft/sec)
4.76	6	484	15.3	6.21	7.82	1.11	17.9	7.73	1.53	3110	
		484	14.1	6.54	8.24	1.20	6.60	4.92	1.53	3110	
		485	15.6	6.13	7.72	1.14	13.4	7.44	1.40	3400	
		485	16.8	6.52	8.21	1.05	9.97	6.59	1.48	3220	
Arithmetic mean			15.4	6.35	8.00	1.12			1.48	3210	
s			±1.1	±0.22	±0.26	±0.06			±0.06	±140	
s (%)			±7.3	±3.5	±3.2	±5.3			±4.0	±4.4	
s_m			±0.56	±0.11	±0.13	±0.03			±0.03	±68	
s_m (%)			±3.6	±1.7	±1.6	±2.7			±2.0	±2.1	
7.94	10	484	6.41	4.46	5.62	1.86	5.63	6.39	3.63	2190	1510
		484	6.61	4.26	5.37	1.62	7.10	6.23	3.62	2190	1520
		485	6.87	5.52	6.95	1.77	7.11	6.97	3.62	2190	1430
		485	7.10	4.60	5.80	1.63	10.1	7.80	3.74	2120	1410
Arithmetic mean			6.75	4.71	5.94	1.72			3.65	2170	1470
s			±0.30	±0.56	±0.70	±0.12			±0.06	±34	±56
s (%)			±4.4	±12	±12	±7.0			±1.6	±1.6	±3.8
s_m			±0.15	±0.28	±0.35	±0.06			±0.03	±18	±28
s_m (%)			±2.2	±5.9	±5.9	±3.5			±0.8	±0.8	±1.9
11.91	15	484	3.12	2.92	3.68	2.11	3.42	6.50	6.33	1880	1470
		485	3.35	2.62	3.30	1.82	6.26	8.94	6.48	1840	1420
Arithmetic mean			3.24	2.77	3.49	1.96			6.40	1860	1440
15.87	20	484	2.65	2.33	2.94	2.26	4.11	8.10	9.39	1690	1290
		485	2.55	2.07	2.61	1.95	6.82	11.0	9.63	1650	1260
Arithmetic mean			2.60	2.20	2.78	2.10			9.51	1670	1280

* Shot number repeated where more than one gage used at a particular location.

TABLE 5

RESULTS OF AIR-BLAST MEASUREMENTS - 0.5-LB CHARGES

$D/W^{1/3} = 0.585$; BOTTOM MATERIAL - SAND

CHARGE POSITION - MID-DEPTH (Z = -0.5D)

Gage Distance (ft)	Reduced Distance λ (ft/lb$^{1/3}$)	Shot No.*	Peak Pressure (psi)	Positive Impulse (lb-ms/in^2)	Reduced Positive Impulse (lb-ms/in^2/lb$^{1/3}$)	Positive Duration (ms)	Negative Impulse (lb-ms/in^2)	Negative Duration (ms)	Arrival Time (ms)	Avg Velocity Charge to Gage (ft/sec)	Avg Velocity Gage to Gage (ft/sec)
4.76	6	489	3.19	2.11	2.66	1.57	8.90	9.75	3.09	1540	
		489	3.38	2.29	2.89	1.90	3.14	5.56	3.24	1470	
		490	3.94	2.16	2.72	1.40	8.71	10.35	2.87	1660	
		490	3.63	2.15	2.71	1.50	4.12	6.80	3.17	1500	
Arithmetic mean			3.54	2.18	2.74	1.59			3.09	1540	
s			±0.32	±0.08	±0.10	±0.22			±0.16	±80	
s (%)			±9.0	±3.7	±3.6	±14			±5.2	±5.2	
s_m			±0.16	±0.04	±0.05	±0.11			±0.08	±40	
s_m (%)			±4.5	±1.8	±1.8	±6.9			±2.6	±2.6	
7.94	10	489	1.95	1.79	2.26	1.97			5.64	1410	1290
		490	2.43	1.87	2.36	1.73	2.16	4.81	5.71	1390	1190
Arithmetic mean			2.19	1.83	2.31	1.85			5.68	1400	1240
11.91	15	489	1.42	1.57	1.98	2.33			8.77	1360	1270
		490	1.81	1.17	1.47	2.09	2.34	7.72	8.90	1340	1240
Arithmetic mean			1.62	1.37	1.72	2.21			8.84	1350	1260
15.87	20	489	1.26	1.21	1.52	2.36	1.37	5.88	12.22	1300	1150
		490	1.30	1.03	1.30	2.22	2.16	8.47	12.20	1300	1200
Arithmetic mean			1.28	1.12	1.41	2.29			12.21	1300	1180

* Shot number repeated where more than one gage used at a particular location.

TABLE 6

RESULTS OF AIR-BLAST MEASUREMENTS - 4-LB CHARGES

$D/W^{1/3}$ = 0.585; BOTTOM MATERIAL - SAND

CHARGE POSITION - ABOVE SURFACE (Z = 0.5D)

Gage Distance (ft)	Reduced Distance λ $(ft/lb^{1/3})$	Shot No.*	Peak Pressure (psi)	Positive Impulse $(lb\text{-}ms/in^2)$	Reduced Positive Impulse $(lb\text{-}ms/in^2/lb^{1/3})$	Positive Duration (ms)	Negative Impulse $(lb\text{-}ms/in^2)$	Negative Duration (ms)	Arrival Time (ms)	Avg Velocity Charge to Gage (ft/sec)	Avg Velocity Gage to Gage (ft/sec)
9.52	6	547	32.6	19.6	12.4	2.36			2.12	4490	
		547	29.3	18.3	11.5	2.25	4.65	3.80	1.94	4910	
		548	47.2	22.3	14.1	2.65	32.7	10.73	1.97	4830	
		548	34.4	16.8	10.6	1.65	13.3	5.35	1.89	5040	
Arithmetic mean			35.9	19.2	12.2	2.23			1.98	4820	
S			±7.8	±2.3	±1.4	±0.42			±0.10	±240	
S (%)			±22	±12	±12	±19			±5.0	±5.0	
S_m			±3.9	±1.2	±0.76	±0.21			±0.05	±120	
S_m (%)			±11	±6.2	±6.2	±9.4			±2.5	±2.5	
15.87	10	547	7.50	9.65	6.08	3.62			5.72	2770	1680
		547	8.14	10.5	6.61	3.49			5.98	2650	1640
		548	9.60	10.9	6.89	4.03			5.49	2890	1800
		548	9.71	10.7	6.73	3.34			5.86	2710	1600
Arithmetic mean			8.74	10.4	6.58	3.62			5.76	2760	1680
S			±1.1	±0.56	±0.36	±0.30			±0.22	±100	±86
S (%)			±12	±5.4	±5.5	±8.3			±3.8	±3.7	±5.1
S_m			±0.55	±0.28	±0.18	±0.15			±0.11	±51	±43
S_m (%)			±6.3	±2.7	±2.7	±4.1			±1.9	±1.8	±2.6
23.81	15	547	3.36	6.89	4.34	4.36	6.44	14.99	10.51	2260	1700
		548	3.73	6.58	4.15	6.23	5.81	9.70	11.26	2120	1420
Arithmetic mean			3.54	6.74	4.24	5.30			10.88	2190	1560
31.75	20	547	2.15	4.88	3.07	5.31	4.59	13.33	18.06	1760	1050
		548	2.53	5.76	3.63	7.13	3.51	10.18	17.17	1850	1340
Arithmetic mean			2.34	5.32	3.35	6.22			17.62	1800	1200

* Shot number repeated where more than one gage used at a particular location.

TABLE 7

RESULTS OF AIR-BLAST MEASUREMENTS - 4-LB CHARGES

$D/W^{1/3}$ = 0.585; BOTTOM MATERIAL - SAND

CHARGE POSITION - AT SURFACE (Z = 0)

Gage Distance (ft)	Reduced Distance λ (ft/lb$^{1/3}$)	Shot No.*	Peak Pressure (psi)	Positive Impulse (lb/ms/in^2)	Reduced Positive Impulse (lb-ms/in^2/lb$^{1/3}$)	Positive Duration (ms)	Negative Impulse (lb-ms/in^2)	Negative Duration (ms)	Arrival Time (ms)	Avg Velocity Charge to Gage (ft/sec)	Avg Velocity Gage to Gage (ft/sec)
9.52	6	543	18.2	14.6	9.23	2.66	19.4	9.24	3.54	2690	
		543	15.5	11.0	6.95	1.99	19.2	8.91	3.45	2760	
		544	17.4	15.2	9.54	2.72	10.5	7.78	3.53	2700	
		544	15.8	13.6	8.55	2.93			3.59	2650	
Arithmetic mean			16.7	13.6	8.57	2.58			3.53	2700	
S			±1.3	±1.8	±1.2	±0.40			±0.06	±46	
S (%)			±7.8	±13	±14	±16			±1.7	±1.7	
S_m			±0.65	±0.90	±0.58	±0.20			±0.03	±23	
S_m (%)			±3.9	±6.6	±6.8	±7.8			±0.8	±0.8	
15.87	10	543	7.40	9.37	5.90	3.29	9.37	8.47	7.95	2000	1430
		544	7.70	11.1	7.02	4.35			7.92	2000	1460
Arithmetic mean			7.55	10.2	6.46	3.82			7.94	2000	1440
23.81	15	543	4.02	6.78	4.27	4.28	13.5	16.21	13.59	1750	1410
		544	3.52	6.33	3.99	4.37	9.55	14.98	13.38	1780	1450
Arithmetic mean			3.77	6.56	4.13	4.32			13.48	1760	1430
31.75	20	543	2.85	5.40	3.40	6.63	7.74	16.00	20.27	1570	1190
		544	2.83	6.03	3.80	4.82	5.23	11.77	19.91	1600	1220
Arithmetic mean			2.84	5.72	3.60	5.72			20.09	1580	1200

* Shot number repeated where more than one gage used at a particular location.

TABLE 8

RESULTS OF AIR-BLAST MEASUREMENTS - 4-LB CHARGES

$D/W^{1/3}$ = 0.585; BOTTOM MATERIAL - SAND

CHARGE POSITION - MID-DEPTH (Z = -0.5D)

Gage Distance (ft)	Reduced Distance λ (ft/lb$^{1/3}$)	Shot No.*	Peak Pressure (psi)	Positive Impulse (lb-ms/in^2)	Reduced Positive Impulse (lb-ms/in^2/lb$^{1/3}$)	Positive Duration (ms)	Negative Impulse (lb-ms/in^2)	Negative Duration (ms)	Arrival Time (ms)	Avg Velocity Charge to Gage (ft/sec)	Avg Velocity Gage to Gage (ft/sec)
9.52	6	541	3.63	3.85	2.43	2.72			6.70	1420	
		541	3.72	3.87	2.44	3.09			6.60	1440	
		542	3.90	4.75	2.99	3.13			6.63	1440	
		542	3.41	4.11	2.59	3.37			6.82	1400	
Arithmetic mean			3.66	4.14	2.61	3.08			6.69	1420	
s			±0.20	±0.42	±0.26	±0.28			±0.10	±20	
s (%)			±5.4	±10	±10	±9.1			±1.5	±1.4	
s_m			±0.10	±0.21	±0.13	±0.14			±0.05	±10	
s_m (%)			±2.7	±5.1	±5.0	±4.5			±0.7	±0.7	
15.87	10	541	2.25	3.28	2.07	3.22			11.84	1340	1240
		541	2.44	3.19	2.01	3.50			11.93	1330	1190
		542	2.51	3.42	2.15	3.48			11.63	1360	1270
		542	2.84	4.15	2.61	4.37			11.78	1350	1280
Arithmetic mean			2.51	3.51	2.21	3.64			11.80	1340	1240
s			±0.24	±0.44	±0.28	±0.50			±0.12	±14	±40
s (%)			±9.6	±12	±13	±14			±1.0	±1.0	±3.2
s_m			±0.12	±0.22	±0.14	±0.25			±0.06	±7.0	±20
s_m (%)			±4.8	±6.3	±6.3	±6.9			±0.5	±0.5	±1.6
23.81	15	541	2.48	3.78	2.38	3.75	15.2	17.30	18.43	1290	1210
		542	1.76	2.65	1.67	4.04			18.08	1320	1250
Arithmetic mean			2.12	3.22	2.02	3.90			18.26	1300	1230
31.75	20	541	1.39	1.90	1.20	4.09	6.49	14.90	25.21	1260	1170
		542	1.45	1.81	1.14	3.02	7.68	14.30	25.29	1260	1100
Arithmetic mean			1.42	1.86	1.17	3.56			25.25	1260	1140

* Shot number repeated where more than one gage used at a particular location.

TABLE 9

RESULTS OF AIR-BLAST MEASUREMENTS - 16-LB CHARGES

$D/W^{1/3}$ = 0.585; BOTTOM MATERIAL - SAND

CHARGE POSITION - ABOVE SURFACE (Z = 0.5D)

Gage Distance (ft)	Reduced Distance λ ($ft/lb^{1/3}$)	Shot No.*	Peak Pressure (psi)	Positive Impulse ($lb\text{-}ms/in^2$)	Reduced Positive Impulse ($lb\text{-}ms/in^2/lb^{1/3}$)	Positive Duration (ms)	Negative Impulse ($lb\text{-}ms/in^2$)	Negative Duration (ms)	Arrival Time (ms)	Avg Velocity Charge to Gage (ft/sec)	Avg Velocity Gage to Gage (ft/sec)
15.12	6	562	44.0	43.1	17.1	3.47			3.15	4800	
		562	37.9	27.0	10.7	1.98			3.15	4800	
		565	28.1	36.8	14.6	4.58			3.29	4600	
		565	42.6	34.2	13.6	2.12			3.08	4910	
Arithmetic mean			38.2	35.3	14.0	3.04			3.17	4780	
S			±7.2	±6.7	±2.8	±1.2			±0.08	±130	
S (%)			±19	±19	±20	±40			±2.5	±2.7	
S_m			±3.6	±3.3	±1.4	±0.61			±0.04	±65	
S_m (%)			±9.4	±9.3	±10	±20			±1.3	±1.4	
25.20	10	562	11.4	13.0	5.16	4.17			8.82	2860	1780
		562	9.84	15.3	6.07	3.85			8.80	2860	1780
		565	9.90	18.5	7.34	5.35			9.19	2740	1710
		565	10.5	14.5	5.75	3.62			9.00	2800	1700
Arithmetic mean			10.4	15.3	6.08	4.25			8.95	2820	1740
S			±0.72	±2.3	±0.92	±0.76			±0.18	±58	±44
S (%)			±6.9	±15	±15	±18			±2.0	±2.0	±2.5
S_m			±0.36	±1.2	±0.46	±0.38			±0.09	±29	±22
S_m (%)			±3.3	±7.8	±7.6	±8.9			±1.0	±1.0	±1.3
37.80	15	562	4.07	13.5	5.34	11.30	4.64	9.24	18.19	2080	1340
		565	3.99	12.9	5.11	9.47	4.97	16.60	19.21	1970	1250
Arithmetic mean			4.03	13.2	5.22	10.40			18.70	2020	1300
50.40	20	562	2.64	10.0	3.97	11.60	4.02	12.30	28.21	1790	1260
		565	2.50	10.8	4.28	10.50	8.48	14.00	29.71	1700	1200
Arithmetic mean			2.57	10.4	4.12	11.00			28.96	1740	1230

* Shot number repeated where more than one gage used at a particular location.

TABLE 10

RESULTS OF AIR-BLAST MEASUREMENTS - 16-LB CHARGES

$D/W^{1/3} = 0.585$; BOTTOM MATERIAL - SAND

CHARGE POSITION - AT SURFACE (Z = 0)

Gage Distance (ft)	Reduced Distance λ (ft/lb$^{1/3}$)	Shot No.*	Peak Pressure (psi)	Positive Impulse (lb-ms/in^2)	Reduced Positive Impulse (lb-ms/in^2/lb$^{1/3}$)	Positive Duration (ms)	Negative Impulse (lb-ms/in^2)	Negative Duration (ms)	Arrival Time (ms)	Avg Velocity Charge to Gage (ft/sec)	Avg Velocity Gage to Gage (ft/sec)
15.12	6	566	14.5	17.0	6.75	3.55	48.7	18.63	4.35	3480	
		566	14.1	14.2	5.63	2.90	23.0	15.63	4.45	3400	
		567	14.9								
		567	15.3								
		568	18.6	22.4	8.89	5.12	21.7	10.40	3.71	4080	
		568	15.7	23.0	9.14	4.86	11.8	6.54	4.17	3630	
Arithmetic mean			15.5	19.2	7.60	4.11			4.17	3650	
S			±1.6	±4.7	±1.7	±1.1			±0.32	±110	
S (%)			±10	±24	±22	±26			±7.7	±3.0	
S_m			±0.66	±2.4	±0.85	±0.53			±0.16	±55	
S_m (%)			±4.3	±12	±11	±13			±3.8	±1.5	
25.20	10	566	4.99	14.6	5.77	6.67	19.1	18.37	11.16	2260	1480
		566	5.01	15.8	6.29	7.20	8.9	12.13	11.68	2160	1390
		567	5.71								
		567	6.10								
		568	4.80	15.5	6.15	7.99	16.5	16.04	10.90	2310	1400
		568	5.05	13.5	5.37	7.36			11.24	2240	1430
Arithmetic mean			5.28	14.8	5.90	7.30			11.24	2240	1420
S			±0.51	±1.0	±0.42	±0.54			±0.32	±62	±40
S (%)			±9.6	±6.8	±7.1	±7.4			±2.8	±2.8	±2.8
S_m			±0.21	±0.52	±0.21	±0.27			±0.16	±31	±20
S_m (%)			±4.0	±3.5	±3.6	±3.7			±1.4	±1.4	±1.4
37.80	15	566	3.30	9.60	3.81	6.76	14.9	19.10	20.04	1890	1460
		567	3.25								
		568	2.70	8.82	3.50	7.05	14.7	20.90	20.86	1810	1290
Arithmetic mean			3.08	9.21	3.66	6.90			20.45	1850	1380
S			±0.33								
S (%)			±11								
S_m			±0.19								
S_m (%)			±6.2								
50.40	20	566	2.65	8.58	3.41	7.85	14.8	22.39	31.24	1610	1120
		567	2.55								
		568	2.28	9.76	3.87	8.44	12.1	21.52	32.05	1570	1130
Arithmetic mean			2.49	9.17	3.64	8.14			31.64	1590	1120
S			±0.19								
S (%)			±7.6								
S_m			±0.11								
S_m (%)			±4.4								

* Shot number repeated where more than one gage used at a particular location.

TABLE 11

RESULTS OF AIR-BLAST MEASUREMENTS - 16-LB CHARGES

$D/W^{1/3}$ = 0.585; BOTTOM MATERIAL - SAND

CHARGE POSITION - MID-DEPTH (Z = -0.5D)

Gage Distance (ft)	Reduced Distance λ ($ft/lb^{1/3}$)	Shot No.*	Peak Pressure (psi)	Positive Impulse ($lb\text{-}ms/in^2$)	Reduced Positive Impulse ($lb\text{-}ms/in^2/lb^{1/3}$)	Positive Duration (ms)	Negative Impulse ($lb\text{-}ms/in^2$)	Negative Duration (ms)	Arrival Time (ms)	Avg Velocity Charge to Gage (ft/sec)	Avg Velocity Gage to Gage (ft/sec)
15.12	6	571	3.78	10.0	3.97	5.62	7.05	11.39	10.34	1460	
		572	3.69	7.37	2.92	4.58	5.13	10.29	10.42	1450	
		572	3.97	9.21	3.66	5.18			10.29	1470	
Arithmetic mean			3.81	8.86	3.52	5.13			10.35	1460	
S			±0.14	±1.4	±0.54	±0.54			±0.07	±10	
S (%)			±3.7	±16	±15	±10			±0.7	±0.7	
S_m			±0.08	±0.78	±0.31	±0.31			±0.04	±6.0	
S_m (%)			±2.1	±8.8	±8.8	±6.0			±0.4	±0.4	
25.20	10	571	2.59	7.02	2.79	5.94	6.85	10.97	18.54	1360	1230
		571	2.31	6.09	2.42	4.94	8.38	14.90	18.66	1350	
		572	2.49	6.67	2.65	6.29	3.67	9.58	18.77	1340	1210
		572	2.71	5.29	2.10	4.09			18.91	1330	1170
Arithmetic mean			2.52	6.27	2.49	5.32			18.72	1340	1200
S			±0.16	±0.76	±0.30	±1.0			±0.16	±14	±31
S (%)			±6.3	±12	±12	±19			±0.9	±1.0	±2.6
S_m			±0.08	±0.38	±0.15	±0.50			±0.08	±7.0	±18
S_m (%)			±3.2	±6.1	±6.0	±9.4			±0.4	±0.5	±1.5
37.80	15	571	1.61	4.14	1.64	5.17	6.38	18.65	28.52	1320	1270
		572	1.90	4.57	1.81	6.12	6.51	21.71	28.95	1310	1250
Arithmetic mean			1.76	4.36	1.72	5.64			28.74	1320	1260
50.40	20	571	1.46	4.02	1.60	5.54	5.05	18.68	39.51	1280	1150
		572	1.39	3.56	1.41	6.18	4.21	17.48	39.39	1280	1210
Arithmetic mean			1.42	3.79	1.50	5.86			39.45	1280	1180

* Shot number repeated where more than one gage used at a particular location.

TABLE 12

RESULTS OF AIR-BLAST MEASUREMENTS - FIELD TESTS - 32-LB CHARGES

$D/W^{1/3}$ = 0.585; BOTTOM MATERIAL - SAND

CHARGE POSITION - ABOVE SURFACE (Z = 0.5D)

Gage Distance (ft)	Reduced Distance λ ($ft/lb^{1/3}$)	Shot No.*	Peak Pressure (psi)	Positive Impulse ($lb\text{-}ms/in^2$)	Reduced Positive Impulse ($lb\text{-}ms/in^2/lb^{1/3}$)	Positive Duration (ms)	Negative Impulse ($lb\text{-}ms/in^2$)	Negative Duration (ms)	Arrival Time (ms)	Avg Velocity Charge to Gage (ft/sec)	Avg Velocity Gage to Gage (ft/sec)
19.05	6	435	26.4	34.5	10.9	4.00			4.47	4260	
		436	22.5	32.7	10.3	4.59			5.33	3570	
		437	26.3	31.0	9.76	4.26			5.14	3710	
		437	22.5	30.1	9.49	4.33			5.24	3640	
Arithmetic mean			24.4	32.1	10.1	4.30			5.04	3800	
S			±2.2	±1.9	±0.62	±0.24			±0.40	±320	
S (%)			±9.0	±6.0	±6.2	±5.6			±7.9	±8.4	
S_m			±1.1	±0.97	±0.31	±0.12			±0.20	±160	
S_m (%)			±4.5	±3.0	±3.1	±2.8			±4.0	±4.2	
31.75	10	435	9.64	20.5	6.47	9.79			12.43	2550	
		435	9.05	20.8	6.56	6.41			12.69	2500	1540
		436	8.95	20.5	6.45	5.83			13.54	2340	1550
		436	8.63	22.5	7.08	7.03			13.23	2400	1610
		437	9.41	20.8	6.55	5.97			13.03	2440	1610
		437	9.04	23.1	7.26	6.92			13.51	2350	1540
Arithmetic mean			9.12	21.4	6.73	6.99			13.07	2430	1570
S			±0.37	±1.1	±0.34	±1.4			±0.44	±83	±36
S (%)			±4.1	±5.1	±5.0	±20			±3.4	±3.4	±2.3
S_m			±0.15	±0.46	±0.14	±0.59			±0.18	±34	±16
S_m (%)			±1.6	±2.1	±2.1	±8.4			±1.4	±1.4	±1.0
47.62	15	435	4.38								
		436	4.30								
		437	4.93								
Arithmetic mean			4.54								
S			±0.35								
S (%)			±7.7								
S_m			±0.20								
S_m (%)			±4.4								
63.50	20	435	2.87	10.3	3.24	9.25			35.81	1770	
		436	2.11	7.66	2.41	9.43			37.50	1690	
		437	2.11	7.65	2.41	9.63			36.85	1720	
Arithmetic mean			2.36	8.54	2.69	9.44			36.72	1730	
S			±0.43	±1.5	±0.48	±0.19			±0.85	±40	
S (%)			±18	±18	±18	±2.0			±2.3	±2.3	
S_m			±0.25	±0.88	±0.28	±0.11			±0.49	±23	
S_m (%)			±11	±10	±10	±1.2			±1.3	±1.3	

* Shot number repeated where more than one gage used at a particular location.

TABLE 13

RESULTS OF AIR-BLAST MEASUREMENTS - FIELD TESTS - 32-LB CHARGES

$D/W^{1/3} = 0.585$; BOTTOM MATERIAL - SAND

Gage Distance (ft)	Reduced Distance λ (ft/lb$^{1/3}$)	Shot No.*	Peak Pressure (psi)	Positive Impulse (lb-ms/in^2)	Reduced Positive Impulse (lb-ms/in^2/lb$^{1/3}$)	Positive Duration (ms)	Negative Impulse (lb-ms/in^2)	Negative Duration (ms)	Arrival Time (ms)	Avg Velocity Charge to Gage (ft/sec)	Avg Velocity Gage to Gage (ft/sec)
CHARGE POSITION - AT SURFACE (z =0)											
19.05	6	414	19.0	25.6	8.07	3.68			5.80	3280	
31.75	10	414	7.99	22.7	7.16	7.93			14.29	2220	1500
47.62	15	414	3.94	14.6	4.58	9.31			25.67	1860	1400
63.50	20	414	2.65	9.39	2.96	8.98			37.50	1690	1340
CHARGE POSITION - MID-DEPTH (z = -0.5D)											
19.05	6	419 419 424 424	3.70 3.86 3.62 2.99	7.85 9.35 8.15 8.50	2.47 2.95 2.57 2.68	5.26 6.08 5.41 6.32			12.77 11.49 13.60 13.45	1490 1660 1400 1420	
Arithmetic mean			3.54	8.46	2.67	5.77			12.83	1490	
S			±0.38	±0.64	±0.20	±0.52			±0.96	±120	
S (%)			±11	±7.6	±7.5	±9.0			±7.5	±7.9	
S_m			±0.19	±0.32	±0.10	±0.26			±0.48	±59	
S_m (%)			±5.4	±3.8	±3.7	±4.5			±3.7	±4.0	
31.75	10	424 424	2.44 2.47	7.38	2.32	5.91			23.68 23.28	1340 1360	1240 1310
Arithmetic mean			2.46						23.48	1350	1280
47.62	15	419	1.82	5.98	1.88	7.94			36.25	1310	
63.50	20	419	1.45	4.63	1.46	7.68			51.59	1230	1040

* Shot number repeated where more than one gage used at a particular location.

TABLE 14

RESULTS OF AIR-BLAST MEASUREMENTS - FIELD TESTS - 256-LB CHARGES

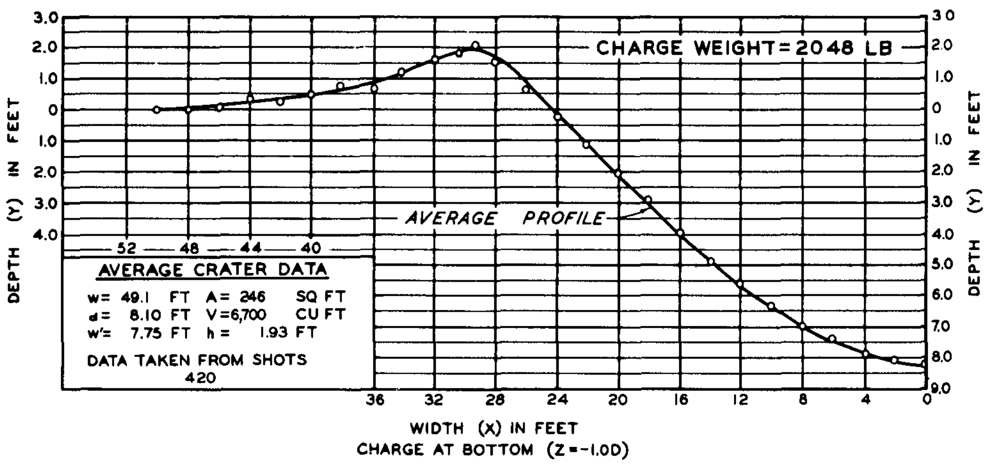
$D/W^{1/3} = 0.585$; BOTTOM MATERIAL - SAND

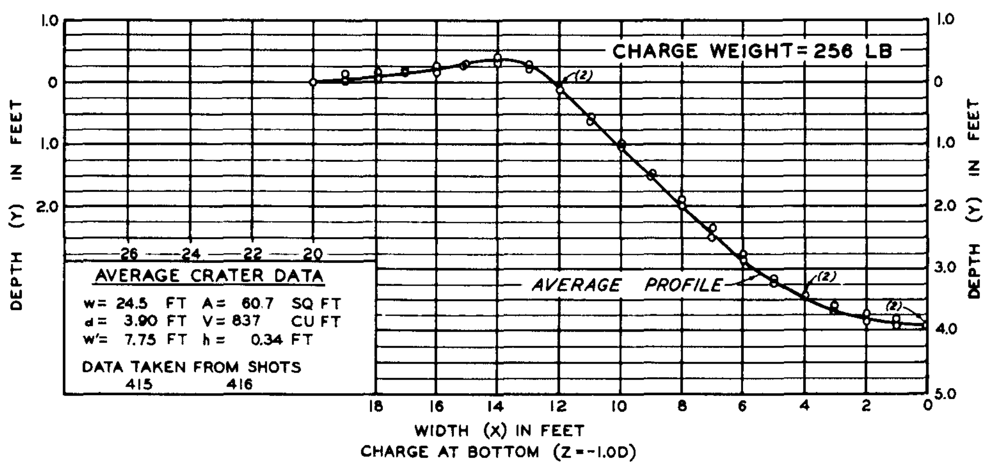
CHARGE POSITION - MID-DEPTH ($Z = -0.5D$)

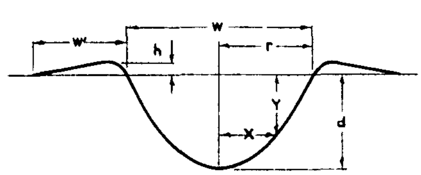
Gage Distance (ft)	Reduced Distance λ ($ft/lb^{1/3}$)	Shot No.*	Peak Pressure (psi)	Positive Impulse ($lb\text{-}ms/in^2$)	Reduced Positive Impulse ($lb\text{-}ms/in^2/lb^{1/3}$)	Positive Duration (ms)	Negative Impulse ($lb\text{-}ms/in^2$)	Negative Duration (ms)	Arrival Time (ms)	Avg Velocity Charge to Gage (ft/sec)	Avg Velocity Gage to Gage (ft/sec)
38.10	6	417	3.84	17.6	2.77	9.26			25.55	1490	
		418	3.78	18.5	2.91	10.4			28.62	1330	
		418	3.92	17.1	2.69	11.0			28.46	1340	
Arithmetic mean			3.85	17.7	2.79	10.2			27.54	1390	
s			±0.07	±0.71	±0.10	±0.88			±1.7	±90	
s (%)			±1.8	±4.0	±3.6	±8.6			±6.2	±6.5	
s_m			±0.04	±0.41	±0.06	±0.51			±1.0	±52	
s_m (%)			±1.0	±2.3	±2.2	±5.0			±3.6	±3.7	
63.50	10	417	2.78	15.3	2.40	9.51			45.63	1390	1260
		417	2.67	12.5	1.97	9.55					
Arithmetic mean			2.72	13.9	2.18	9.53			45.63	1390	1260
95.24	15	417	1.97	11.1	1.75	13.3			72.50	1310	1180
		418	1.80	8.42	1.33	10.5			72.50	1310	
Arithmetic mean			1.88	9.76	1.54	11.9			72.50	1310	1180
126.99	20	417	1.33	8.50	1.34	14.2			100.00	1270	1160
		418	1.48	8.81	1.39	17.2			100.00	1270	1160
Arithmetic mean			1.40	8.66	1.36	15.7			100.00	1270	1160

* Shot number repeated where more than one gage used at a particular location.

PLATES







CRATER DIMENSIONS

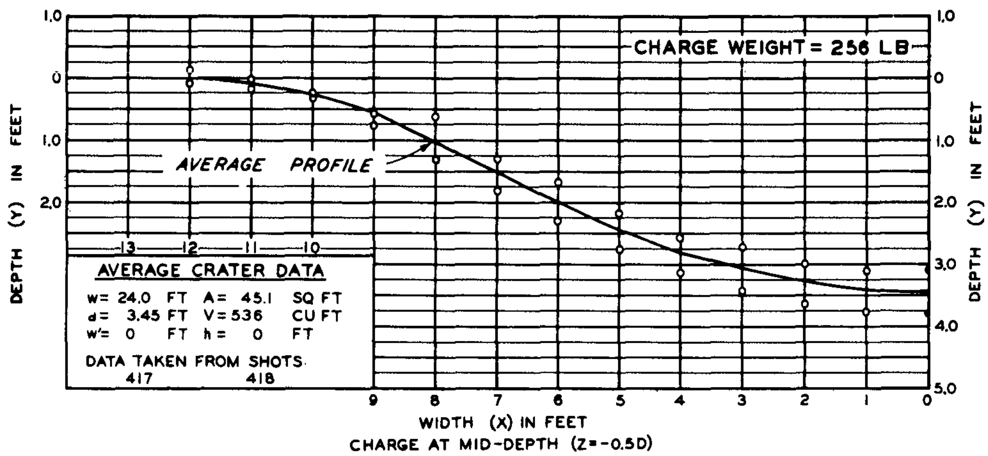
HALF-CRATER PROFILES

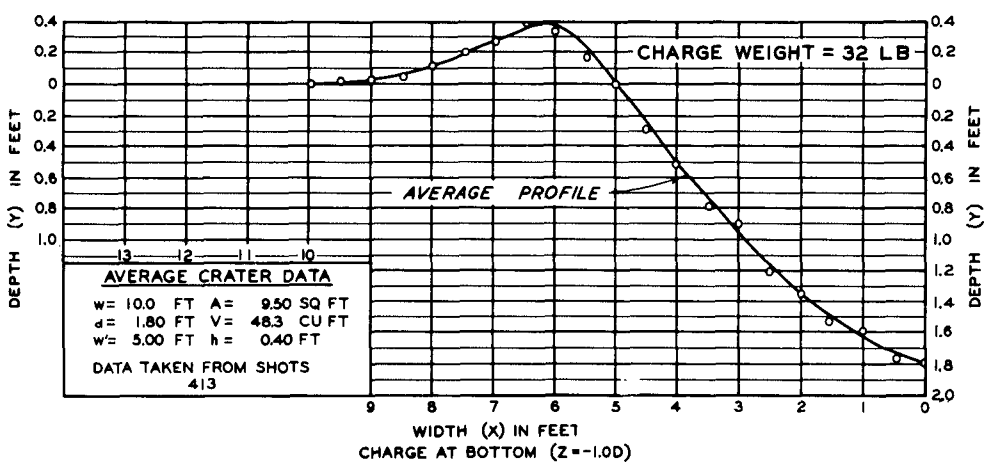
BOTTOM MATERIAL - SAND

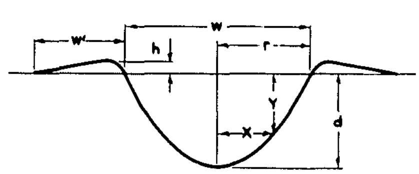
CHARGE POSITION AT BOTTOM

FIELD TESTS

$D/W^{\frac{1}{3}} = 0.585$



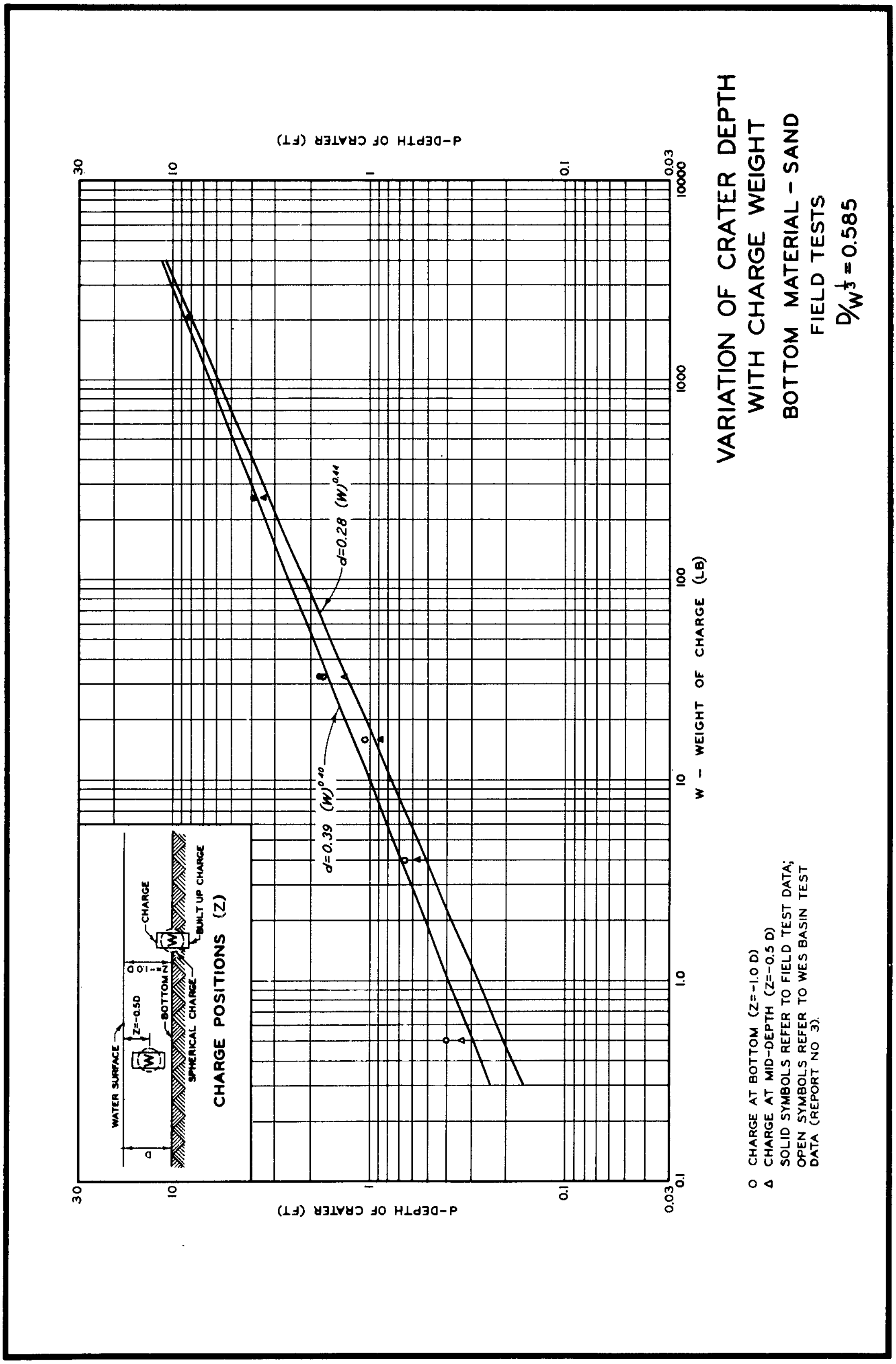


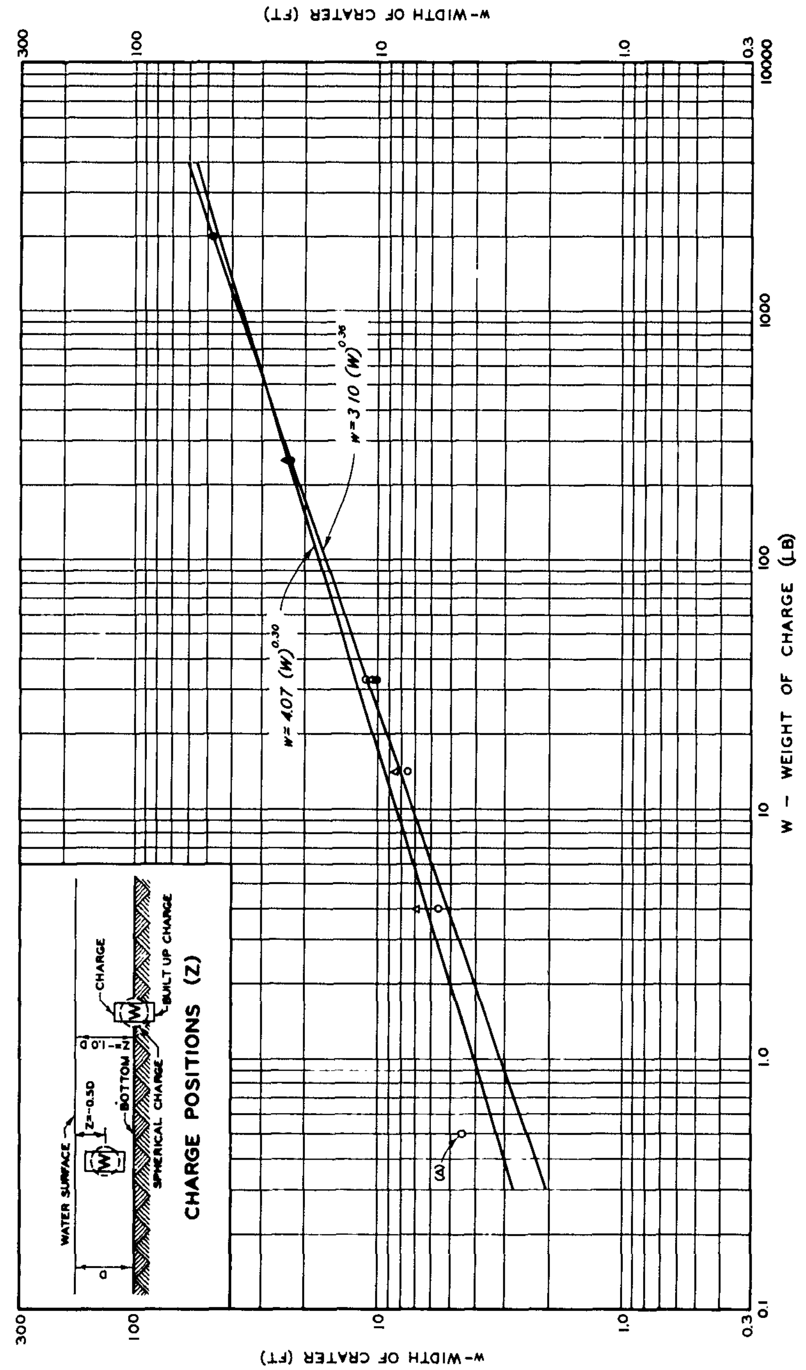


CRATER DIMENSIONS

HALF-CRATER PROFILES
BOTTOM MATERIAL - SAND
CHARGE POSITIONS AS SHOWN
FIELD TESTS
$D/W^{1/3} = 0.585$

PLATE 2


VARIATION OF CRATER DEPTH
WITH CHARGE WEIGHT
BOTTOM MATERIAL - SAND
FIELD TESTS
D/W^1/3 = 0.585
d-DEPTH OF CRATER (FT)
W - WEIGHT OF CHARGE (LB)
d=0.28 (W)^0.44
d=0.39 (W)^0.40
WATER SURFACE
Z=-0.5D
BOTTOM
Z=-1.0D
CHARGE
SPHERICAL CHARGE
BUILT UP CHARGE
CHARGE POSITIONS (Z)
O CHARGE AT BOTTOM (Z=-1.0 D)
Δ CHARGE AT MID-DEPTH (Z=-0.5 D)
SOLID SYMBOLS REFER TO FIELD TEST DATA;
OPEN SYMBOLS REFER TO WES BASIN TEST
DATA (REPORT NO 3).

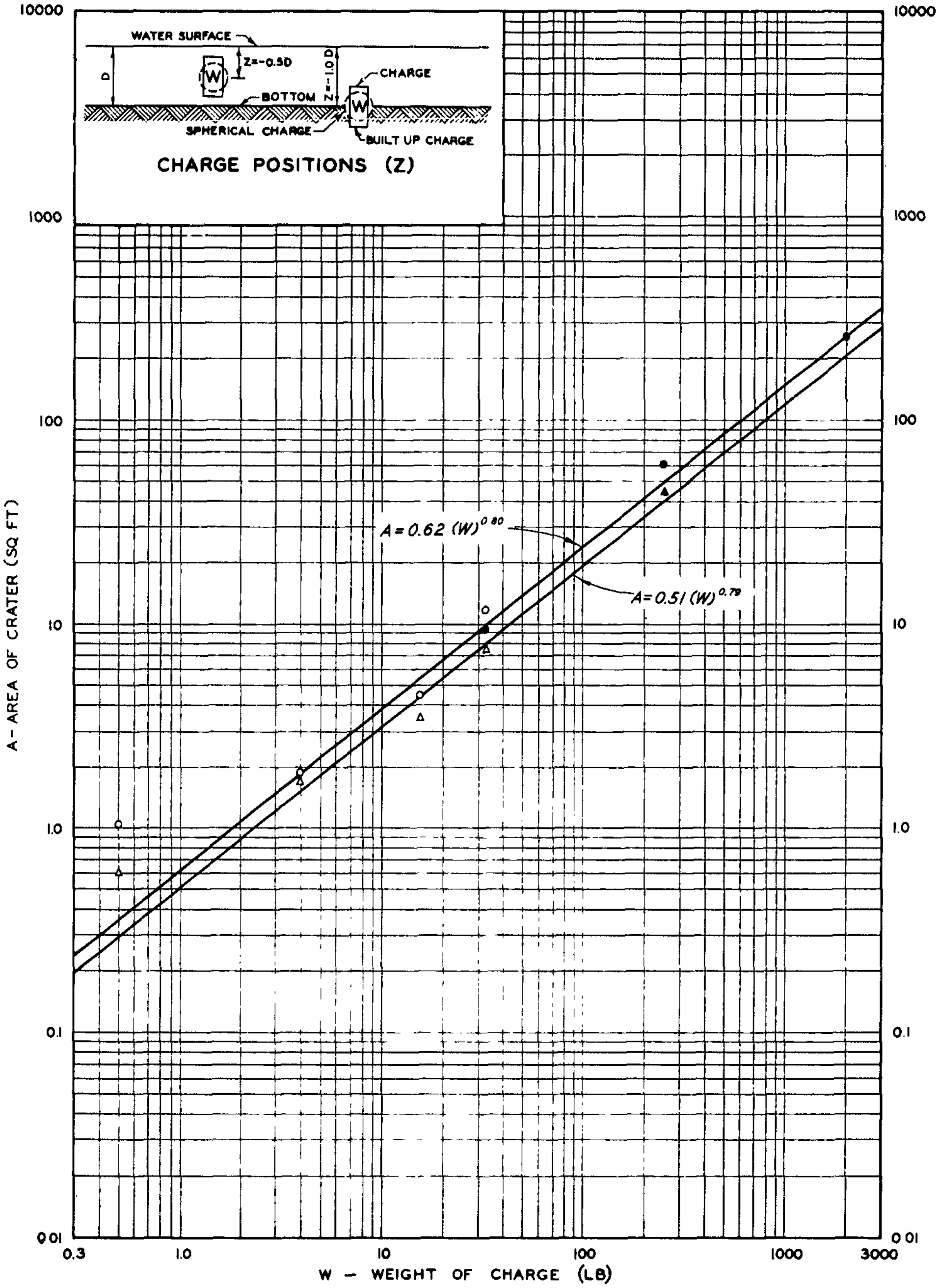


VARIATION OF CRATER WIDTH WITH CHARGE WEIGHT

BOTTOM MATERIAL - SAND
FIELD TESTS
$D/W^{\frac{1}{3}} = 0.585$

- O CHARGE AT BOTTOM (Z = -1.0D)
- Δ CHARGE AT MID-DEPTH (Z = -0.5D)

SOLID SYMBOLS REFER TO FIELD TEST DATA.
OPEN SYMBOLS REFER TO WES BASIN TEST DATA (REPORT NO 3)

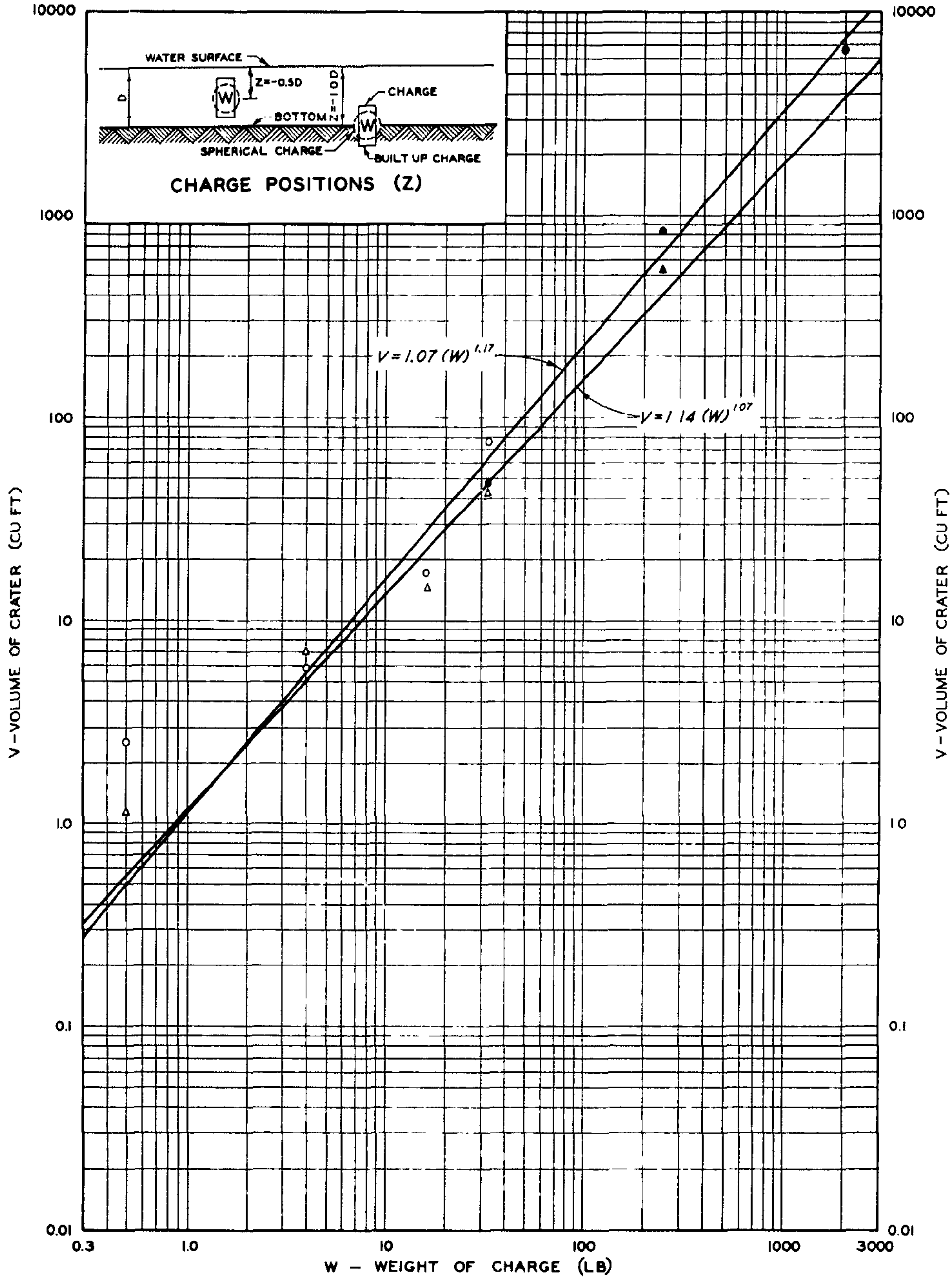


O CHARGE AT BOTTOM (Z=-1.0 D)
Δ CHARGE AT MID-DEPTH (Z=-0.5 D)
SOLID SYMBOLS REFER TO FIELD TEST DATA;
OPEN SYMBOLS REFER TO WES BASIN TEST DATA (REPORT NO. 3).

VARIATION OF CRATER AREA WITH CHARGE WEIGHT

BOTTOM MATERIAL - SAND
FIELD TESTS

$D/W^{\frac{1}{3}} = 0.585$



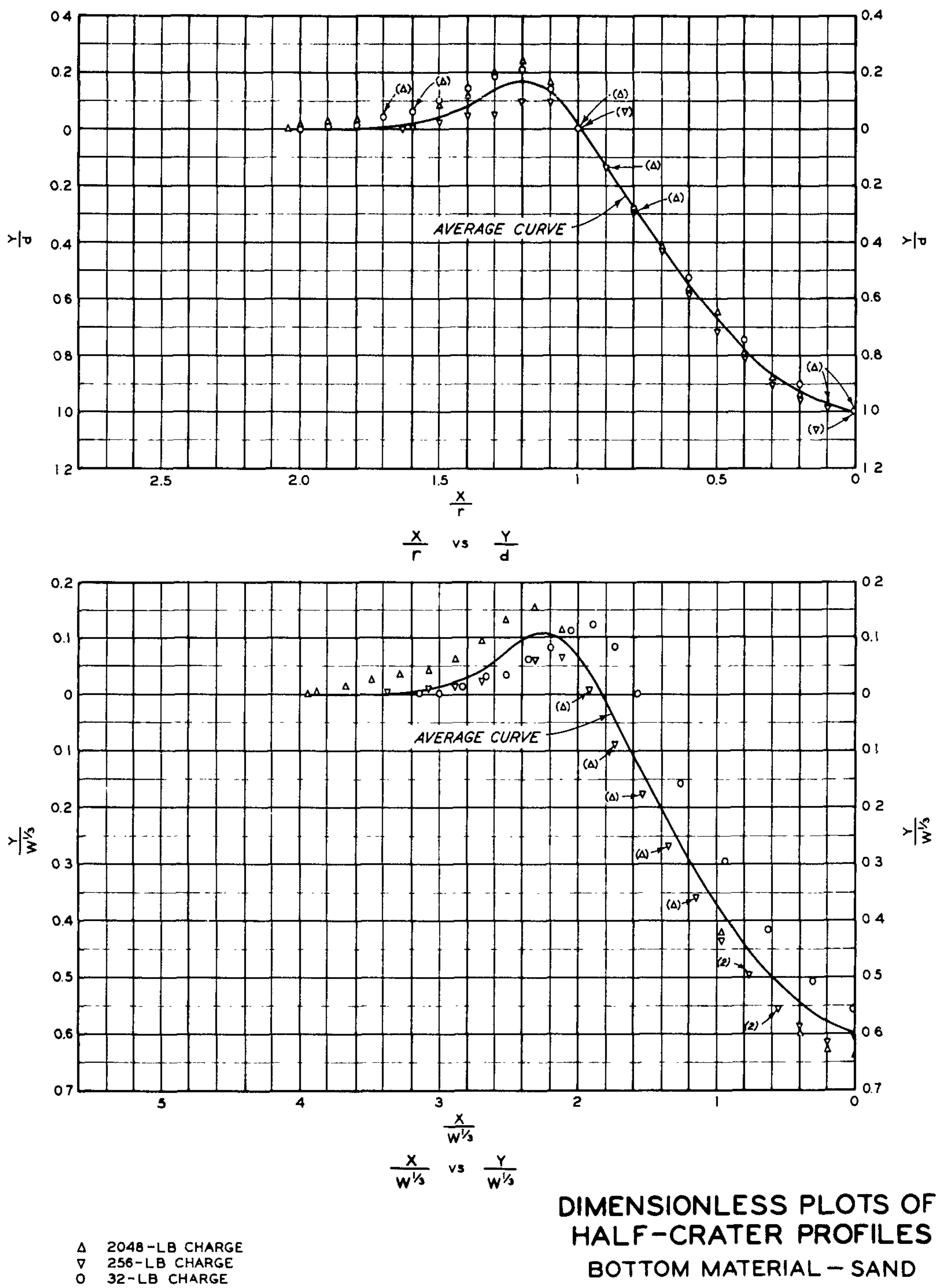
o CHARGE AT BOTTOM (Z=-1.0 D)
Δ CHARGE AT MID-DEPTH (Z=-0.5 D)
SOLID SYMBOLS REFER TO FIELD TEST DATA;
OPEN SYMBOLS REFER TO WES BASIN TEST DATA (REPORT NO 3).

VARIATION OF CRATER VOLUME WITH CHARGE WEIGHT

BOTTOM MATERIAL - SAND

FIELD TESTS

$D/W^{\frac{1}{3}} = 0.585$



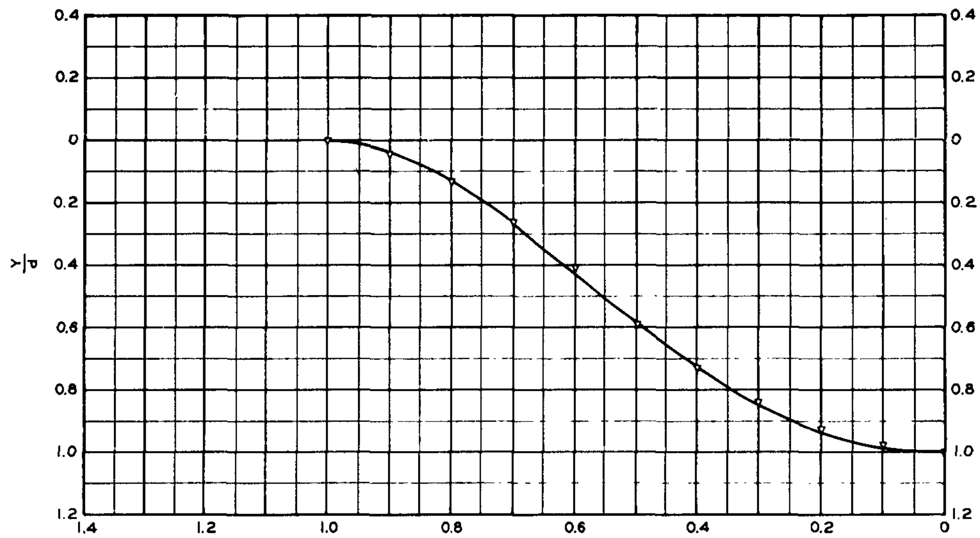
DIMENSIONLESS PLOTS OF HALF-CRATER PROFILES

BOTTOM MATERIAL – SAND

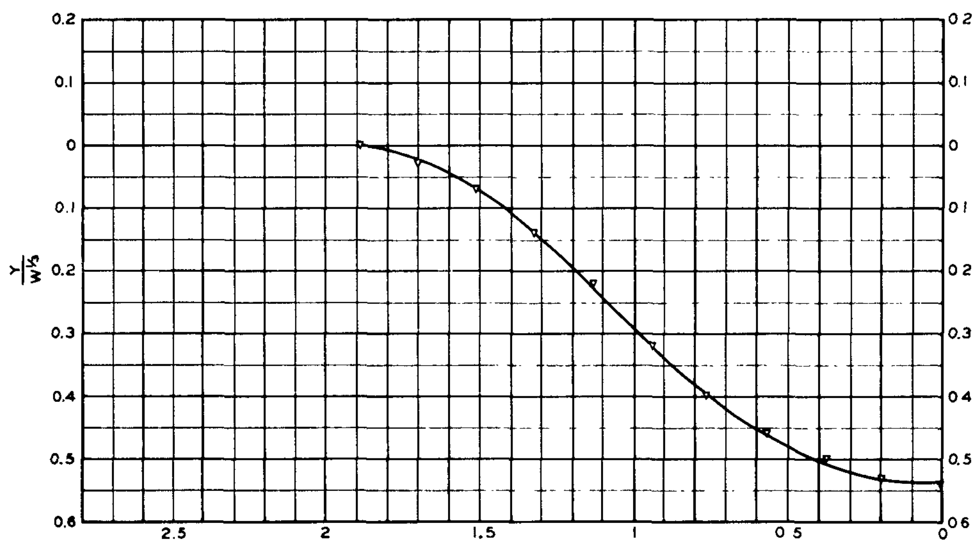
CHARGE AT BOTTOM (Z=-1.0D)

FIELD TESTS

$D/W^{\frac{1}{3}} = 0.585$



X/r vs Y/d



X/W⅓ vs Y/W⅓

▽ 256-LB CHARGE

DIMENSIONLESS PLOTS OF HALF-CRATER PROFILES

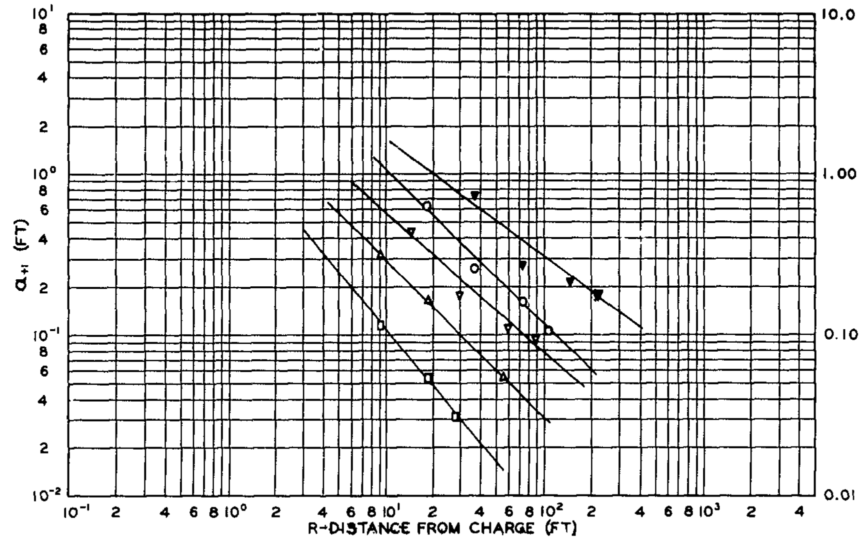
BOTTOM MATERIAL - SAND

CHARGE AT MID-DEPTH (Z=-0.5D)

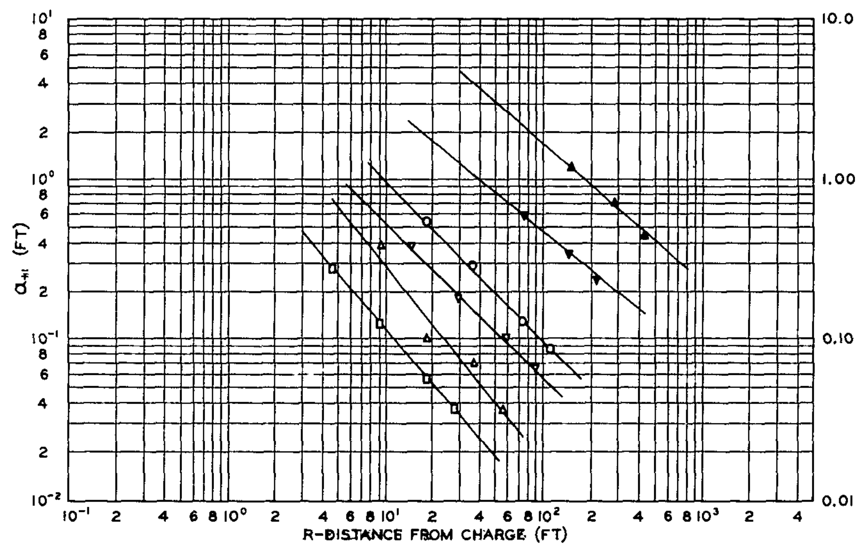
FIELD TESTS

$D/W^{\frac{1}{3}} = 0.585$

PLATE 8



Z=-0.5D



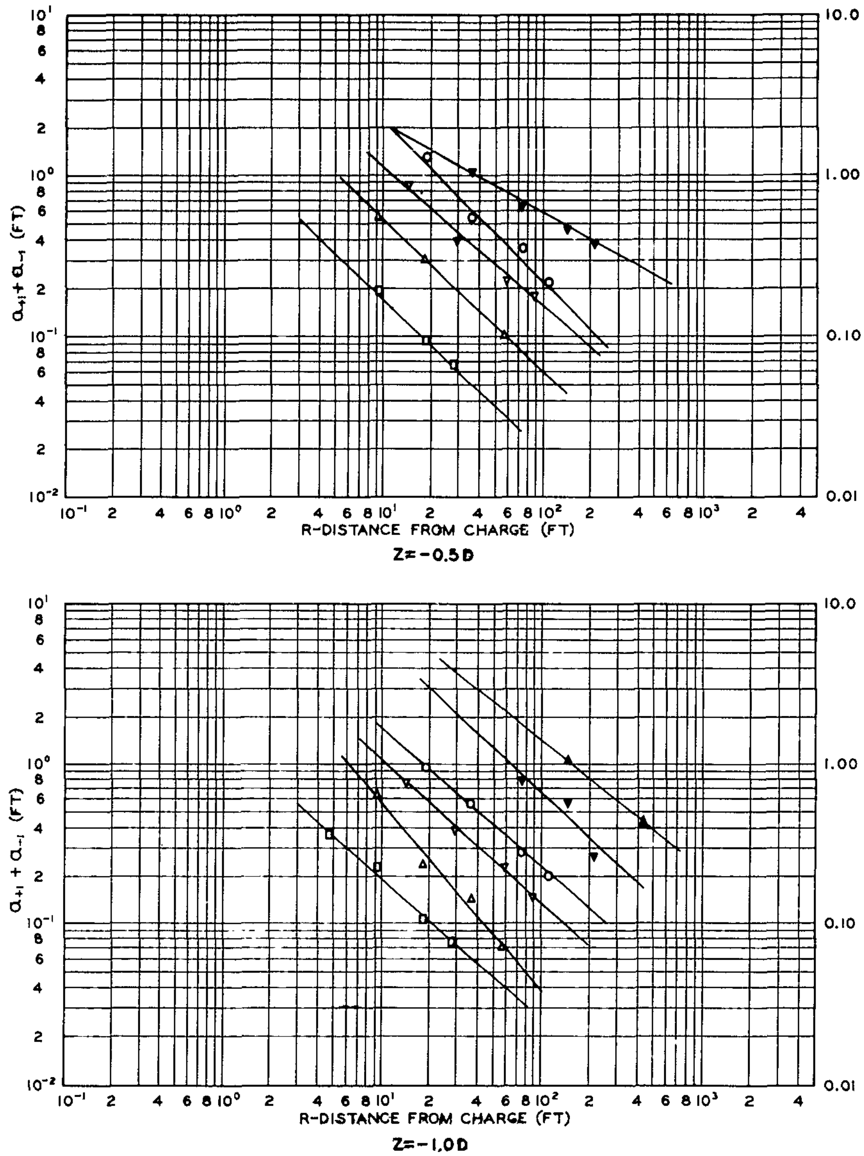
Z=-1.0D

□ 0.5-LB CHARGE
△ 4-LB CHARGE
▽ 16-LB CHARGE
○ 32-LB CHARGE
▼ 256-LB CHARGE
▲ 2048-LB CHARGE
a_{+1} HEIGHT OF CREST ABOVE STILL WATER IN FEET
D DEPTH OF WATER IN FEET
Z CHARGE POSITION

EFFECT OF DISTANCE ON WAVE HEIGHT

FIRST CREST

$D/W^{\frac{1}{3}} = 0.585$



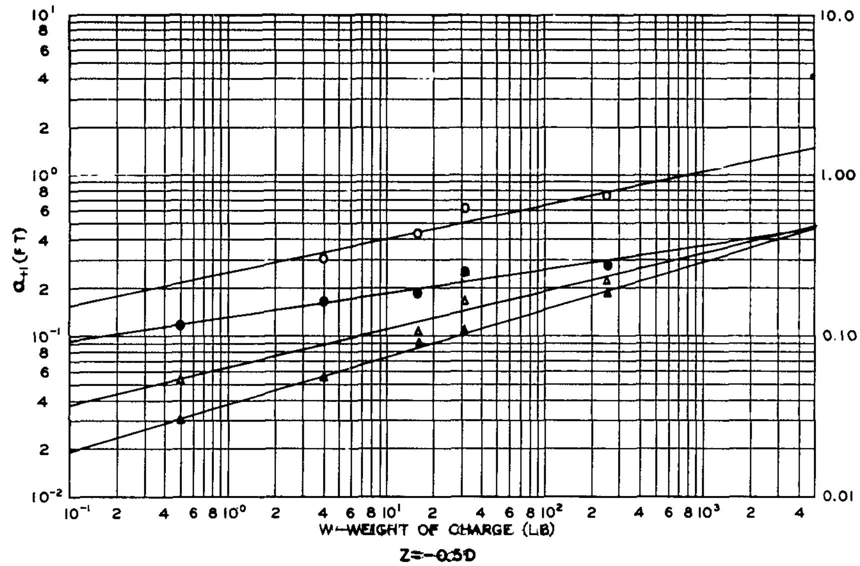
□ 05-LB CHARGE
△ 4-LB CHARGE
▽ 16-LB CHARGE
○ 32-LB CHARGE
▼ 256-LB CHARGE
▲ 2048-LB CHARGE

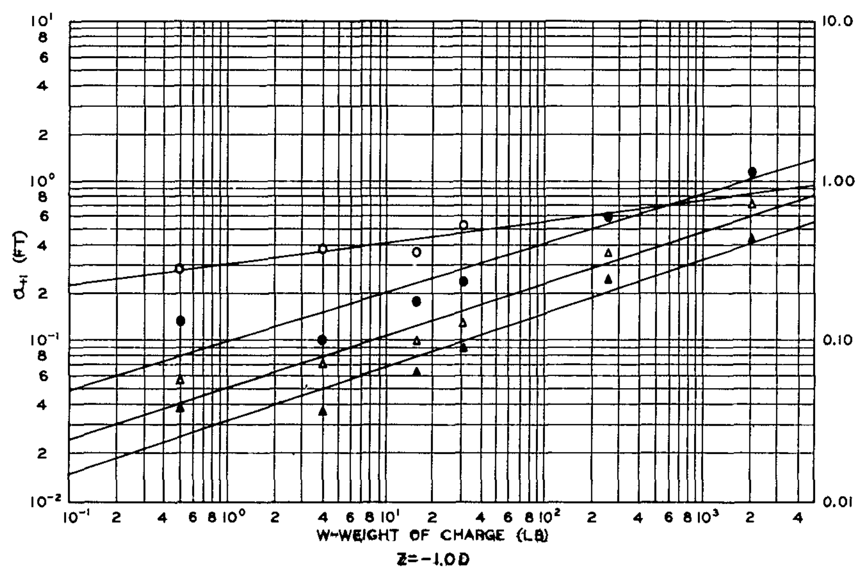
a_{+1} HEIGHT OF CREST ABOVE STILL WATER IN FEET
a_{-1} DEPTH OF TROUGH BELOW STILL WATER IN FEET
$a_{+1} + a_{-1}$ HEIGHT OF WAVE-CREST TO TROUGH IN FEET
D DEPTH OF WATER IN FEET
Z CHARGE POSITION

EFFECT OF DISTANCE ON WAVE HEIGHT

FIRST CREST PLUS FIRST TROUGH

$D/W^{\frac{1}{3}} = 0.585$



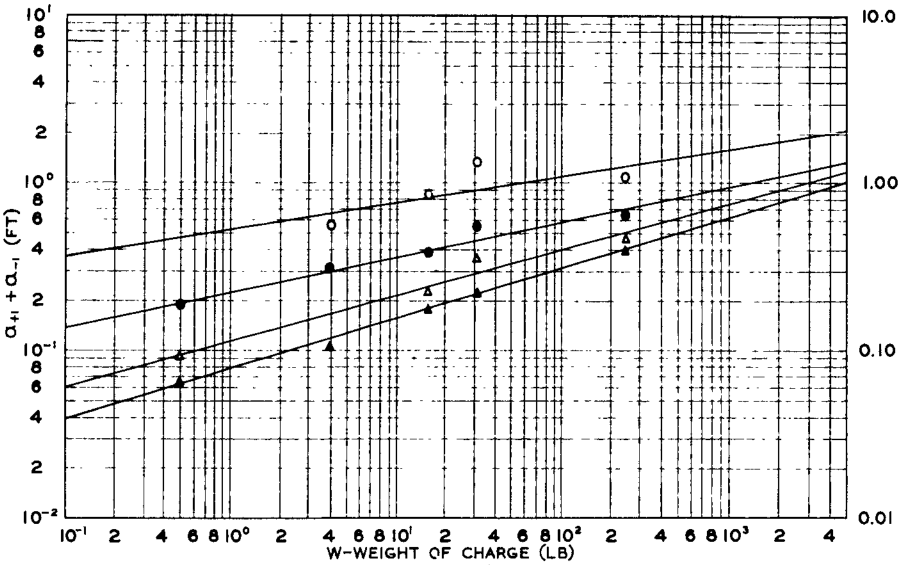


o	$R/D = 10$
●	$R/D = 20$
△	$R/D = 40$
▲	$R/D = 60$
a_{+1}	HEIGHT OF CREST ABOVE STILL WATER IN FEET
R	DISTANCE FROM CHARGE IN FEET
D	DEPTH OF WATER IN FEET
Z	CHARGE POSITION

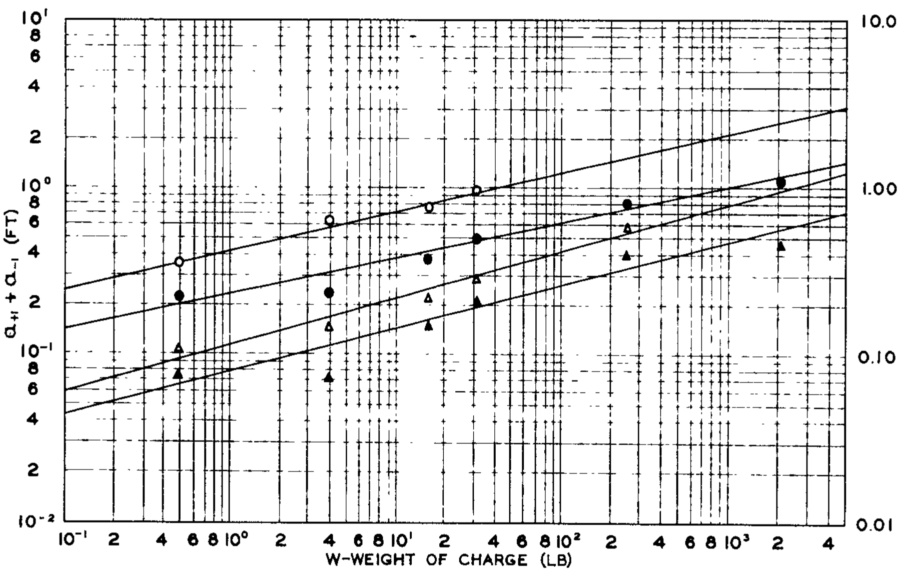
EFFECT OF CHARGE WEIGHT ON WAVE HEIGHT

FIRST CREST

$D/W^{\frac{1}{3}} = 0.585$



Z=−0.5 D



Z=−1.0 D

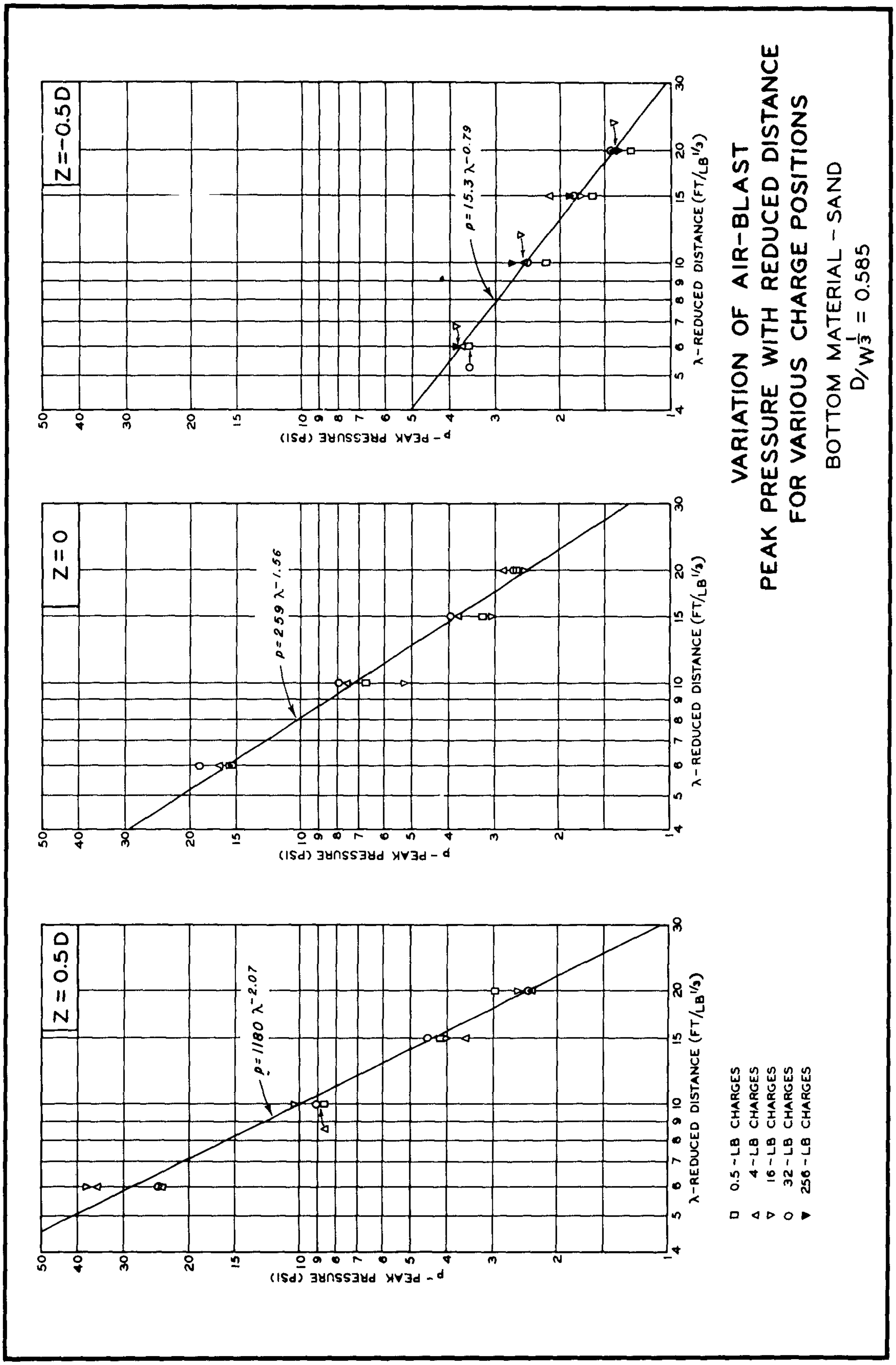
○	$R/D = 10$
●	$R/D = 20$
△	$R/D = 40$
▲	$R/D = 60$
a_{+1}	HEIGHT OF CREST ABOVE STILL WATER IN FEET
a_{-1}	DEPTH OF TROUGH BELOW STILL WATER IN FEET
$a_{+1} + a_{-1}$	HEIGHT OF WAVE-CREST TO TROUGH IN FEET
R	DISTANCE FROM CHARGE IN FEET
D	DEPTH OF WATER IN FEET
Z	CHARGE POSITION

EFFECT OF CHARGE WEIGHT ON WAVE HEIGHT

FIRST CREST PLUS FIRST TROUGH

$D/W^{\frac{1}{3}} = 0.585$

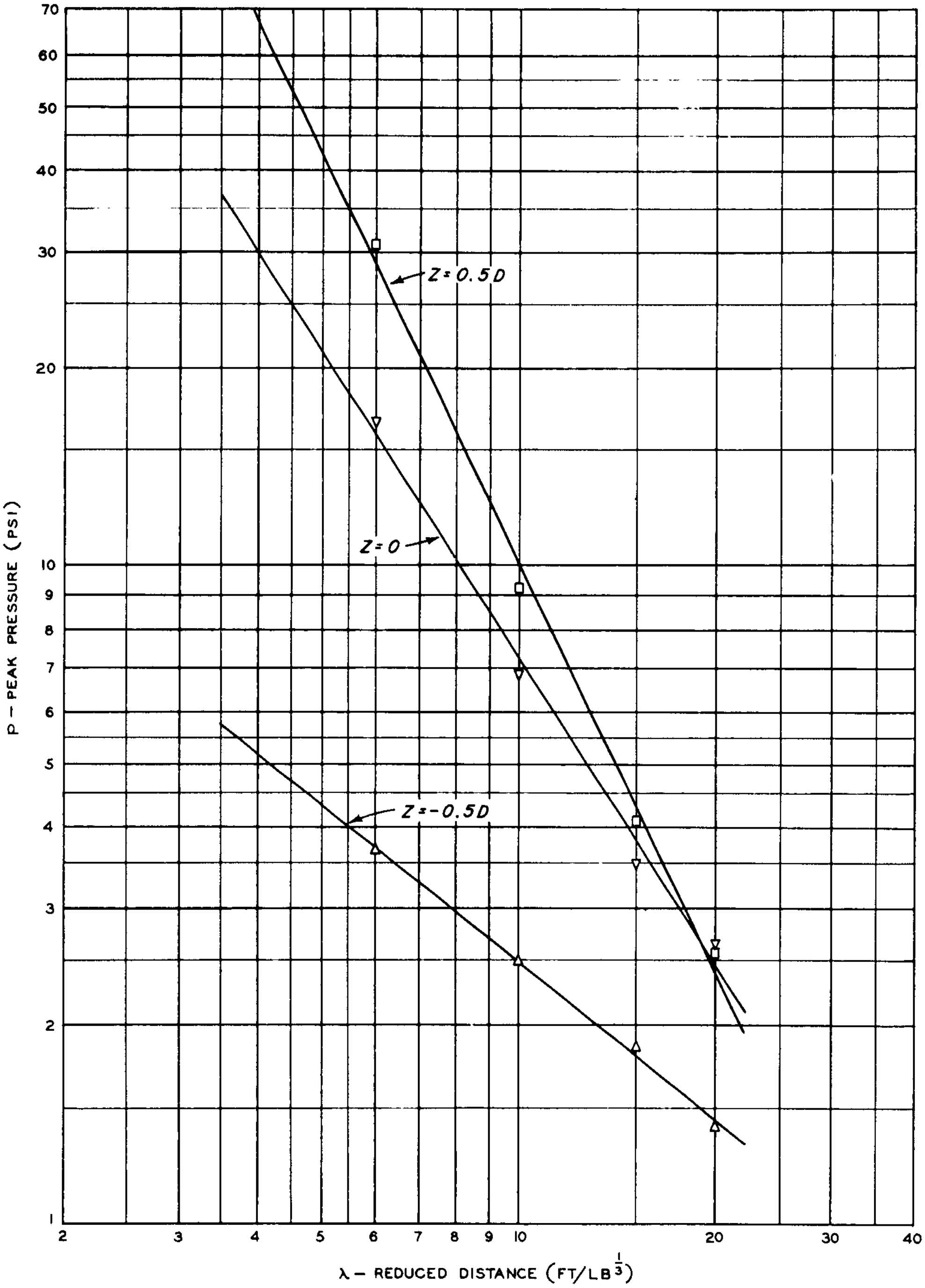
PLATE 12



VARIATION OF AIR-BLAST
PEAK PRESSURE WITH REDUCED DISTANCE
FOR VARIOUS CHARGE POSITIONS

BOTTOM MATERIAL - SAND

$D/W^{\frac{1}{3}} = 0.585$



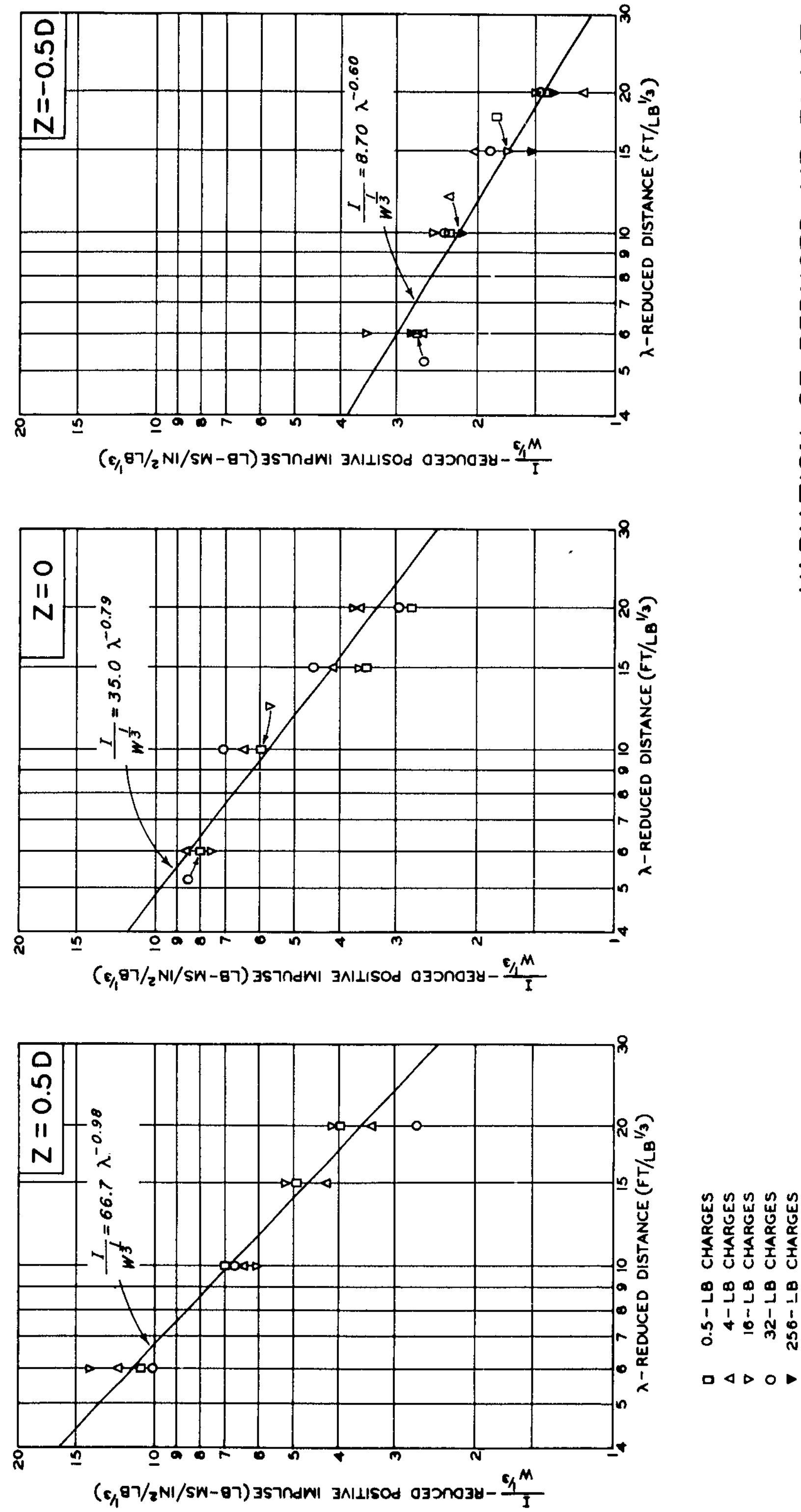
□ CHARGE ABOVE SURFACE (Z=0.5 D)
▽ CHARGE AT SURFACE (Z=0)
△ CHARGE AT MID-DEPTH (Z=-0.5 D)

VARIATION OF AIR-BLAST PEAK PRESSURE WITH REDUCED DISTANCE

BOTTOM MATERIAL - SAND

$D/W^{\frac{1}{3}} = 0.585$

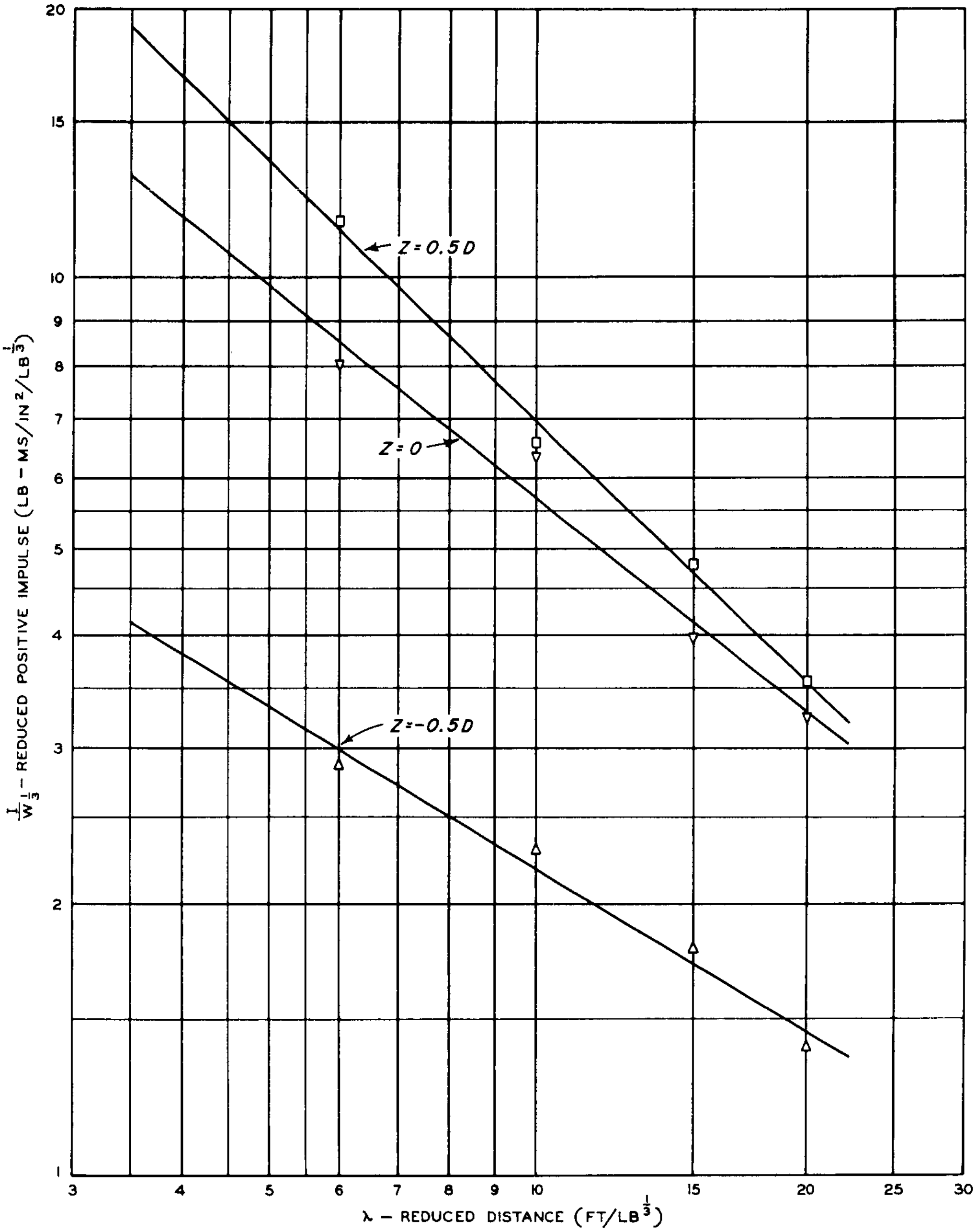
PLATE 14



VARIATION OF REDUCED AIR-BLAST POSITIVE IMPULSE WITH REDUCED DISTANCE FOR VARIOUS CHARGE POSITIONS

BOTTOM MATERIAL - SAND

$D/W^{\frac{1}{3}} = 0.585$

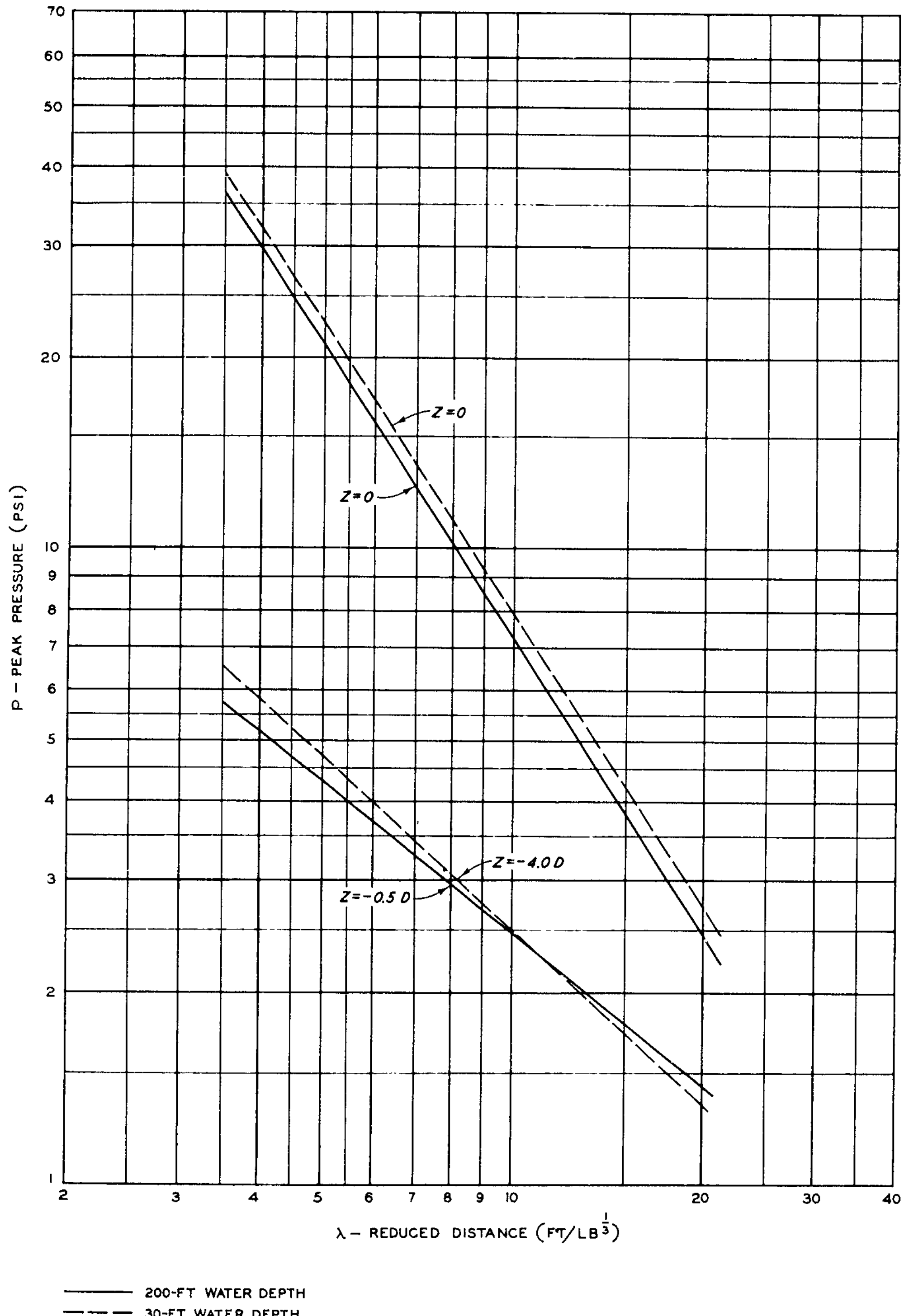


□ CHARGE ABOVE SURFACE (Z=0.5D)
▽ CHARGE AT SURFACE (Z=0)
△ CHARGE AT MID-DEPTH (Z=-0.5D)

VARIATION OF REDUCED AIR-BLAST POSITIVE IMPULSE WITH REDUCED DISTANCE

BOTTOM MATERIAL - SAND

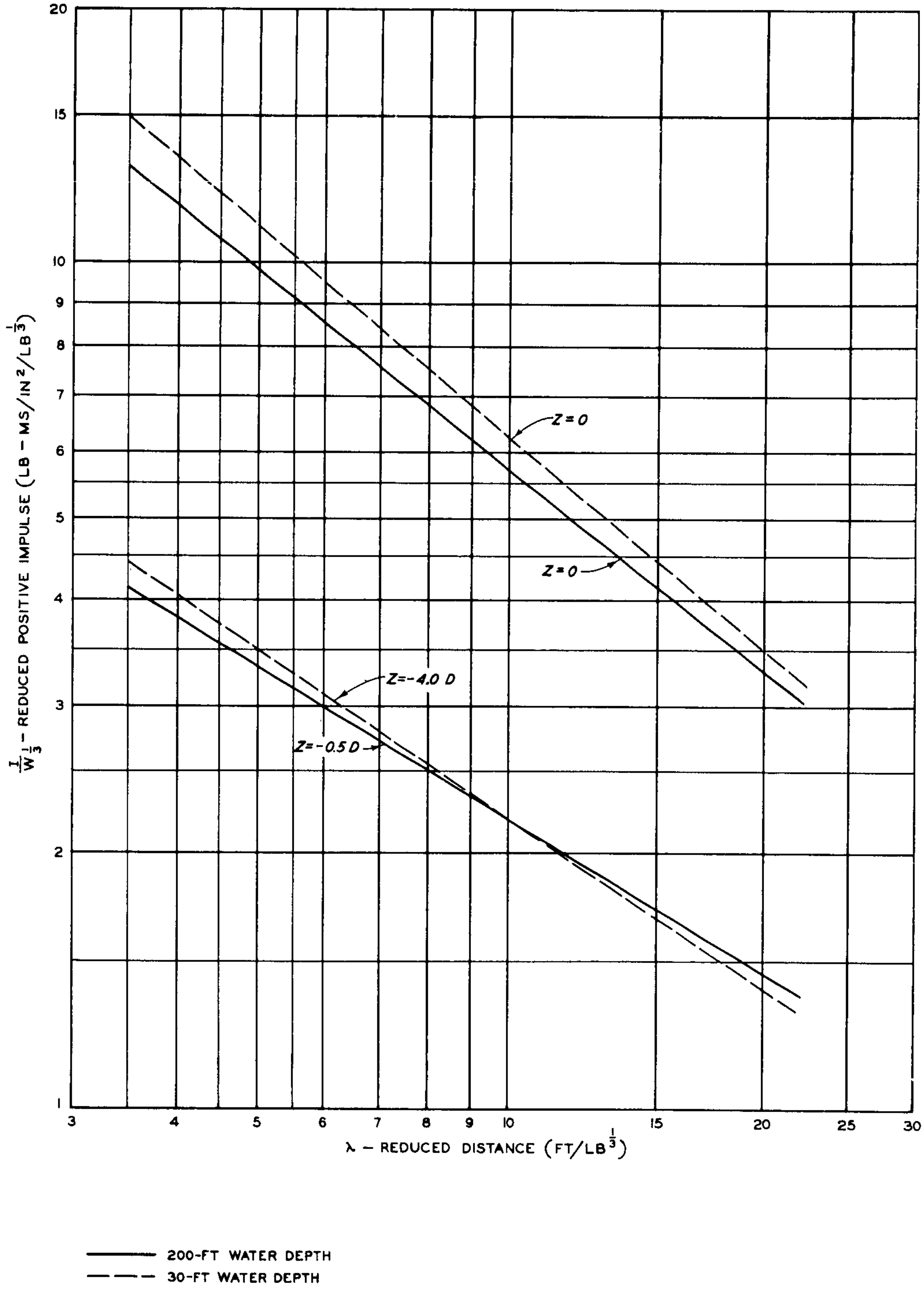
$D/W^{\frac{1}{3}} = 0.585$



COMPARISON OF AIR-BLAST PEAK PRESSURE

SCALED 30-AND 200-FT WATER DEPTHS

BOTTOM MATERIAL – SAND



COMPARISON OF REDUCED
AIR-BLAST POSITIVE IMPULSE
SCALED 30-AND 200-FT WATER DEPTHS
BOTTOM MATERIAL - SAND